NASA CONTRACTOR REPORT

NASA CR - 61010

N64-33880
(ACCESSION NUMBER) (THRU)
88 1
(PAGES) (CODE)
CR 61010 08
(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

FACILITY FORM 602

NASA CR - 61010

APOLLO LOGISTICS SUPPORT SYSTEMS MOLAB STUDIES

Task Report on
Microwave Systems Studies

Prepared under Contract No. NAS8-5307 by

R. A. Moore

HAYES INTERNATIONAL CORPORATION
Missile and Space Support Division
Birmingham, Alabama

OTS PRICE

XEROX $ 3.00
MICROFILM $ .75

For

NASA - GEORGE C. MARSHALL SPACE FLIGHT CENTER
Huntsville, Alabama

October 1964

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1.0 INTRODUCTION

Since mass is of primary concern in space and lunar expeditions, it is necessary to make parametric studies of all systems to determine their capability and approximate mass . It also is necessary to select an optimum system based on mass versus effectiveness (cost and reliability),

This study is an effort to provide some comparison between optimum antenna gain and transmitter power, with a low mass system as the prime objective. Various areas pertinent to the MOLAB communications link were investigated.

Section 2.0 discusses the effects of cosmic radiation (thermal noise and solar activity) on the communications link. Also included is an explanation of the parameters for the link equation.

In section 3.0, the communication system is analyzed in a general nature. The function of the basic components are discussed, along with the effects of electrical and mechanical malfunctions.

The communications link is evaluated in parametric form in section 4.0. Here the effective radiated power as a function of information bandwidth and signal-to-noise ratio is evaluated.

The state-of-the-art of various S-Band transmitters, adaptable to MOLAB usage, is discussed in section 5.0. General operating and state-of-the-art characteristics such as mass , power drain, power output, size, and reliability are described.

Section 6.0 presents a mass -versus-power output expression for state-of-the-art S-Band transmitter systems in the MOLAB power range (10-200 watts). An analysis of various types of antennas is presented in respect to size versus gain. The parabolic reflector is analyzed, and an expression is formulated with antenna mass as a function of reflector diameter or gain. The two expressions, transmitter mass and antenna mass , are combined to produce a total system mass .

A solution is obtained in such a way that a pre-determined effective radiated power requirement, the transmitter, and the antenna may be optimized regarding:

a) Transmitter Mass
b) Transmitter RF Output
c) Antenna Mass
d) Antenna Size (Diameter)
e) Antenna Gain

Section 7.0 is included only as an information study, as it was written prior to the formulation of this specific task order assignment. This section is a point design study for an S-Band communications link on the lunar surface.

LIST OF ILLUSTRATIONS

2.0 MOLAB RF COMMUNICATION PROBLEM AREAS

Certain conditions that are present which can produce variation in the communication system may be classified in two groups. One group is composed of semi-predictable items such as solar noise (flares, winds, etc.) cosmic noise and orientation, with respect to the earth, of objects with various brightness temperatures. The second group consists mainly of malfunctions associated with mechanical and electrical equipment and the extent to which they will effect the communication link. Included in this group are the effects of micrometeorite bombardment.

A study of the two groups will be presented in the following discussion.

2.1 SEMI-PREDICATABLE

The method by which the communication link is effected, by cosmic noise, solar flares, etc., can be shown best in an analysis of RF link equation.

$$ERP = P_T G_T = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{KT_E B \cdot S/N \cdot L \cdot S.F.}{G_R}$$

P_T or ERP (effective radiated power) is the power required to transmit the desired information occupying a band width (B), and has a predetermined signal-to-noise ration)S/N). Both are dependent upon the type of modulation utilized. The quantity $\left(\frac{4\pi R}{\lambda}\right)^2$ is essentially a fixed value, being a function of range (R) and the wave length (λ) of the transmitter carrier frequency.

The value of transmitting antenna gain (G_T), a safety factor assigned to the system, and losses (L) associated with cabling, atmospheric conditions, etc., are fixed design parameters of the RF link.

Boltzman's constant (K) is the thermal noise power existing in the system due to the random motion of electrons that occur in any substance as the temperature is increased above absolute zero (0^oK). The value of this constant is 1.38 x 10^{-23} joules per degree Kelvin.

The effective noise temperature (T_E) of the RF system is a summation of the noise temperatures associated with the ohmic losses in the receiving antenna, type of receiver, solar and cosmic noise, and carrier frequency.

The curve (Figure 1) shows how the equivalent antenna temperature varies with frequency, hot or quiet sky, and the angle which the antenna makes with the horizon. The actual RF signal gain (G_R) of the receiving antenna is a fixed parameter of the system. It is a function of physical size,

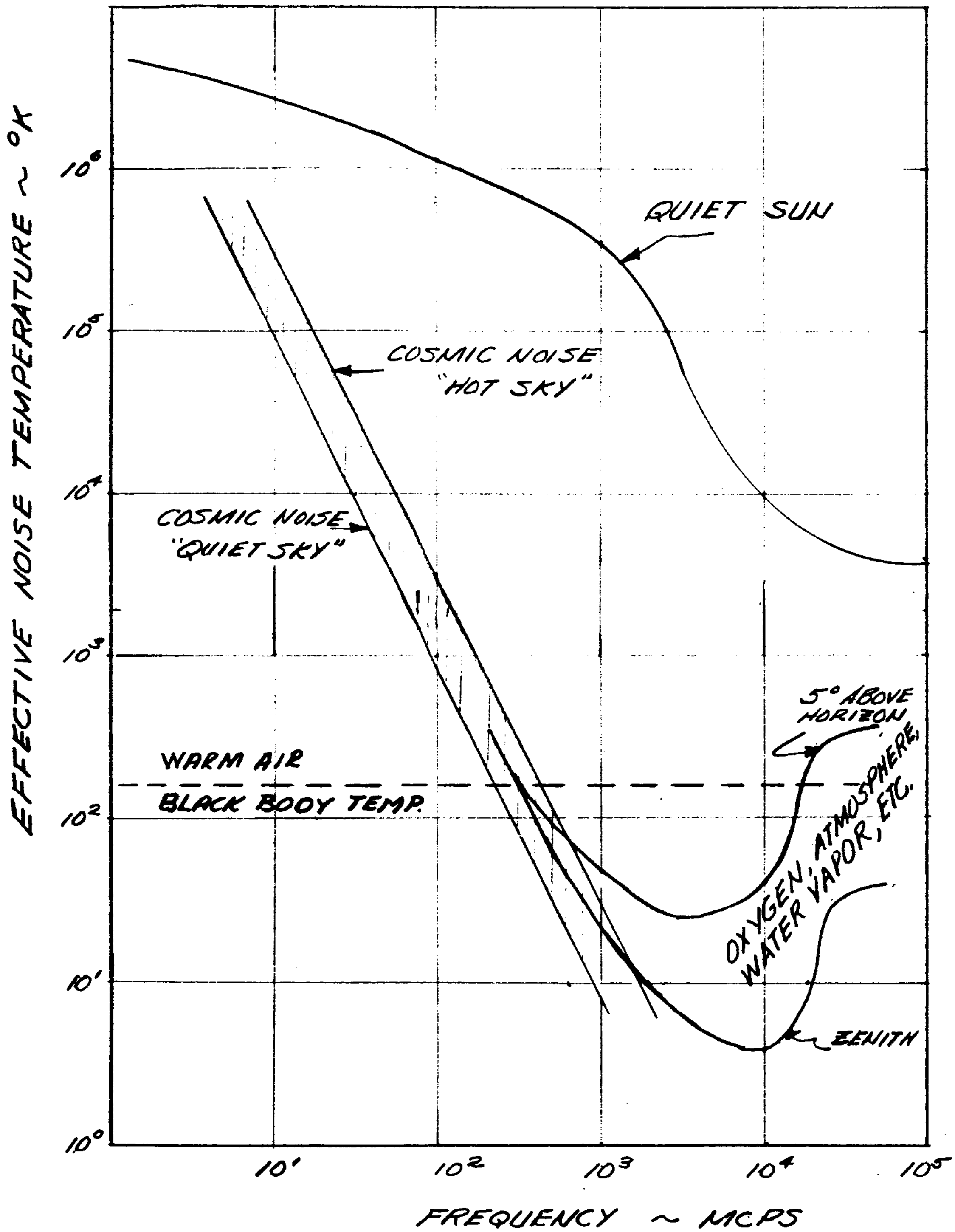


FIGURE 1. FREQUENCY VERSUS EFFECTIVE NOISE TEMPERATURE

transmitter frequency, and effective capture aperture, i.e., the antenna design. This antenna gain determines the solid angle in space, the antenna main beam, and the side-lobes into which the transmitted RF energy can be collected.

The portion or area of the sky that this beam encompasses may include cosmic noise cources, solar noise, etc. These noise sources contribute to the overall effective thermal noise of the system. Thus, the receiving antenna beamwidth and the ability to position this beam at an object in space, such as the moon, will determine the noise temperature present at the receiving antenna terminals.

The effective noise temperature or brightness temperature of the moon has been determined to be approximately $200^{o}K$ at 2300 mcps. (JPL report "Space Programs Summary" No. 37-10, Vol. I). The effective noise temperature of the 25.84 m (85 Ft.) Goldstone antenna and receiver system (wave guide switches, masers, amplifiers, etc.), when referenced to a "quiet sky", has been calculated by JPL (report No. 37-16, Vol III) to be $71.1^{o}K$ at 2300 mcps. Therefore, a total or effective noise temperature of approximately $270^{o}K$, considering the moon as the only contributing noise source, is obtained for the system. This may or not be the situation, as shown by the following example.

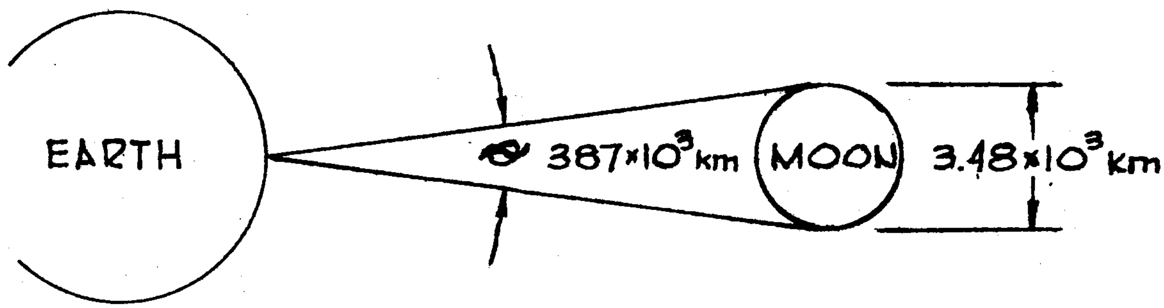
The 25.84 meter (85 ft.) parabolic antennas of the DSIF station has a gain of 53.8 db at 2300 mcps. The half-power or 3 db beamwidths are calculated below, assuming 65 percent aperture efficiency.

$$\text{Gain} = (0.65)\ \frac{4\pi\,(\text{Steradians})}{(\text{B.W.})^2_{3db}} = 2.4 \times 10^5 = 53.8 \text{ db}$$

$$(\text{B.W.})^2_{3db} = \frac{(0.65)\ (4\pi)\ (57.3)^2}{2.4 \times 10^5} = 0.112$$

$$\text{B.W.}_{3db} = 0.334 \text{ degrees}$$

Now, consider the angle, Θ, which the moon makes with a point on the earth.



$$\frac{\Theta}{2} = \text{Arctan}\ \frac{1.74}{387} = \text{Arctan } 0.0045$$

$$\frac{\Theta}{2} = 15 \text{ minutes or } 0.25 \text{ degrees}$$

$$\Theta = 0.50 \text{ degrees}$$

JPL reports a tracking accuracy of 0. 015 degrees for the 25.84 m (85 ft.) antenna. It may be assumed, therefore, that the earth-based receiving antenna (DSIF) will at all times have its beam pointed toward the surface of the moon. Thus, the moon will be the only noise temperature source in the receiving antenna beam.

2.2 SOLAR ACTIVITY

The information which exists on solar activity is very limited. Astronomers have observed and recorded solar (sunspot) activity for many years. It has been observed that sunspot activity occurs in somewhat of a cyclic fluctuation with a periodicity of eleven years. There is some correlation between solar sunspot groups and solar flare activity: all flares are associated with sunspot groups but all sunspots do not necessarily produce flares.

It would be desirable to know the time of occurrence and the intensity of flare activity. Various schemes are being utilized where, by inspection of photographs of sunspot groups, it is possible to predict, within a few days, when solar flares will occur. Accuracies of about 90 percent have been achieved by this means. This method establishes only the probability of flare occurrence, and does not indicate the intensity of such activity. The frequency of solar flare activity will help to determine operation schedules, and the intensity, which is not predictable, will determine the proton radiation density. The solar flare activity will limit the extent of communications between the moon and earth due to contamination of space with excessive proton radiation.

The factors in the communication link that will be effected are signal-to-noise levels and, possibly, the effective noise temperature.

The noise level which determines the carrier signal-to-noise ratio will definitely increase during the period of solar flares and other solar activity. This will decrease effectively the design signal-to-noise level of the link, as the signal level is essentially fixed. The extent to which the system or information will be degraded will depend upon the type of modulation employed (FM, AM, PM etc.). An increase also will be produced in the effective noise temperature recorded at the receiving antenna terminals, due to the increased solar activity.

The system safety factor is used to account for the conditions described (decrease in design signal-to-noise level, increase in noise temperature etc.). This protection is incorporated in the system to accommodate minor increases of noise. If values exceed the designed safety factor of the system, the bandwidth for information necessarily will need to be reduced to obtain usable data.

The intensity of the solar activity will determine the extent to which the communication link can be used during this period. A voice link (2.5 kc) to earth at all times is a minimum requirement. A plot of degree to which an increased effective noise temperature will require an information bandwidth reduction, with other parameters of the link remaining constant, is shown in Figure 2. This plot is for a noise power (PN) of - 100 dbw, where $PN_{(dbw)} = KT_E B$

The effect produced by a decrease in S/N, caused by an increase in noise (N), does not present this type of analogy as the method of modulation (FM or AM) plays a very important role in describing what occurs.

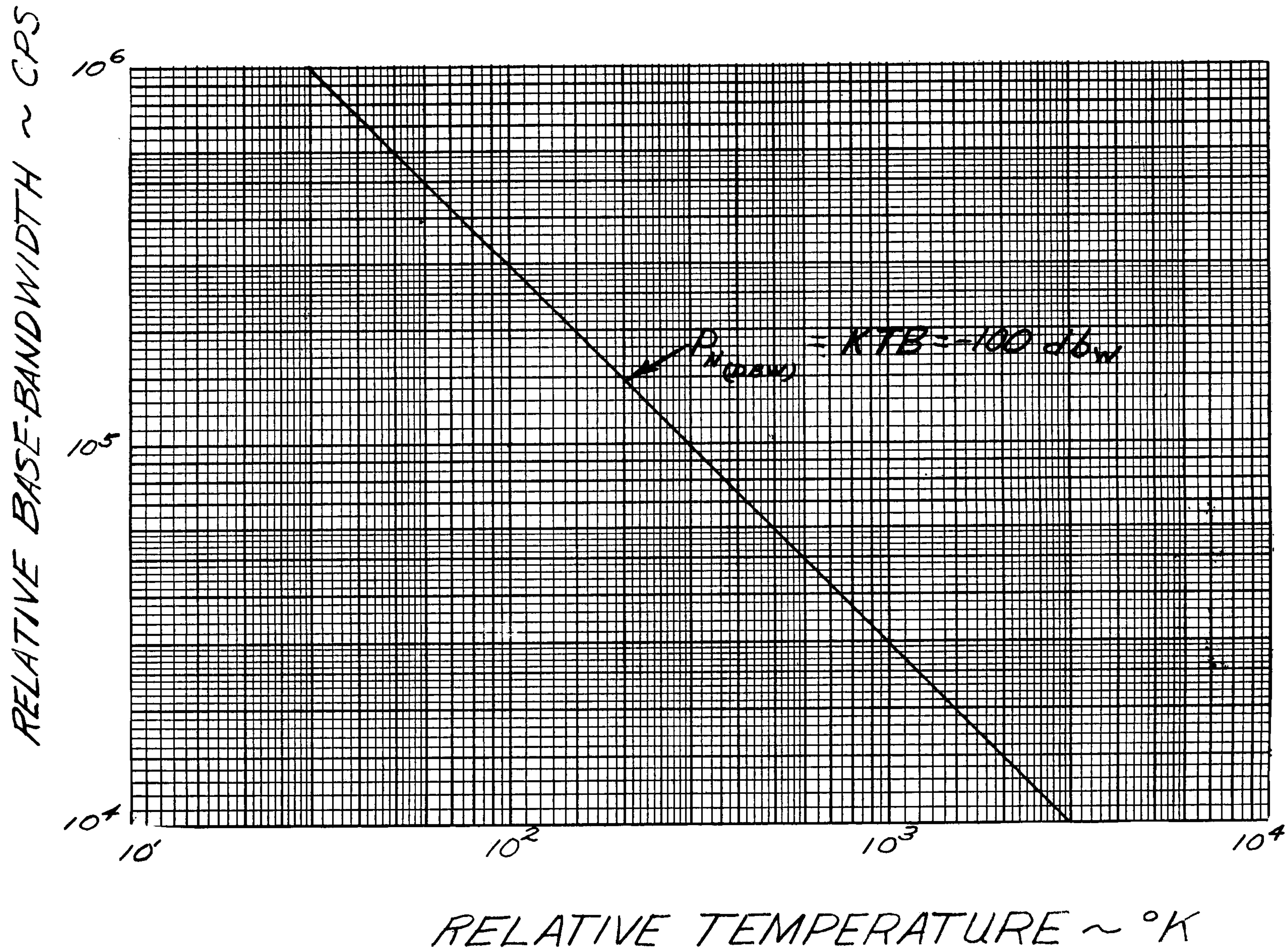


FIGURE 2. RELATIVE EFFECTIVE NOISE VERSUS RELATIVE BASE BANDWIDTH TEMPERATURE

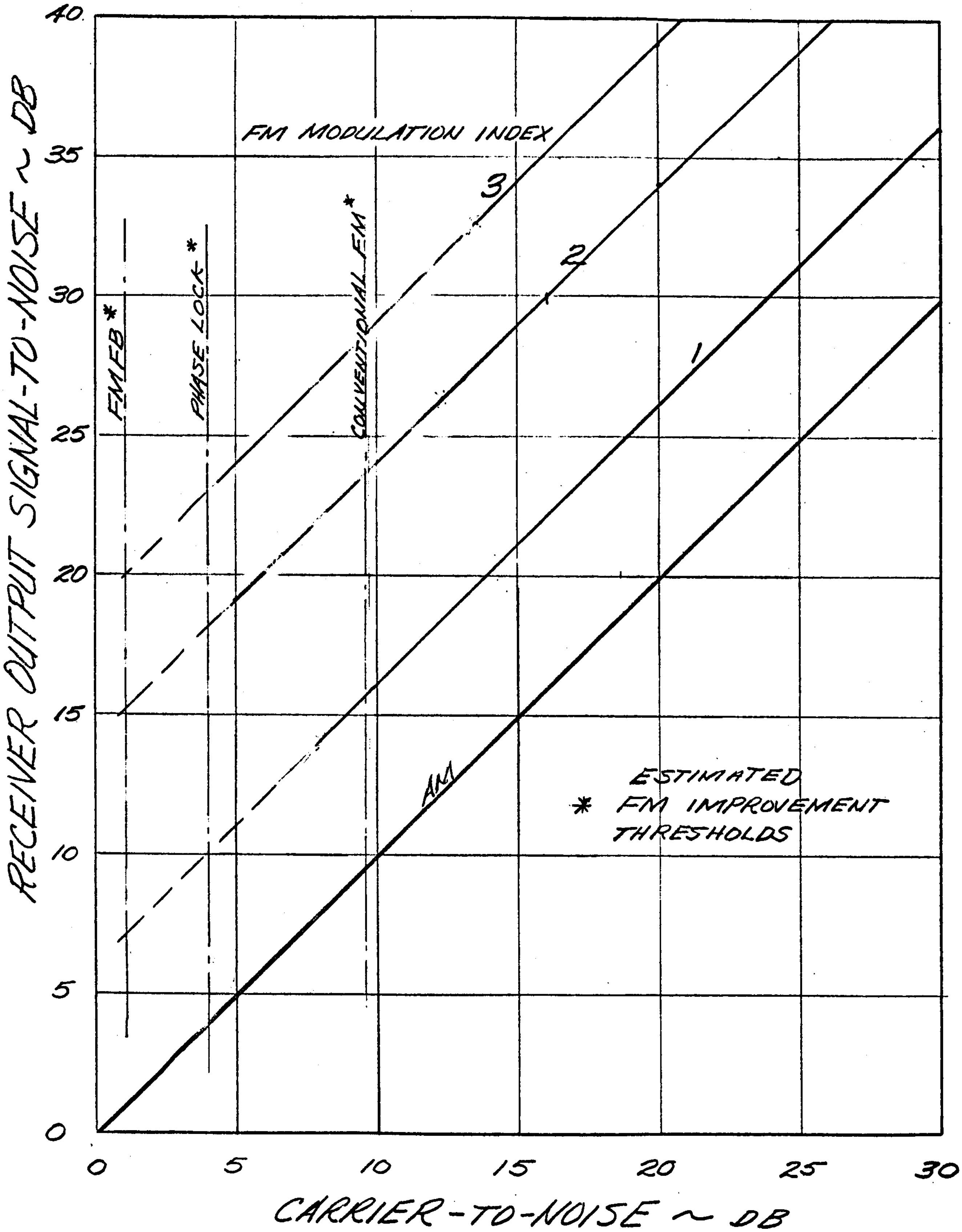


FIGURE 3. RECEIVER SIGNAL-TO-NOISE RATIO VERSUS CARRIER-TO-NOISE RATIO

In an amplitude-modulated system the ratio between signal and noise can be expressed as a linear function with respect to the intelligence delivered, i.e., the higher the ratio the better the quality of information received.

This is not the case in the frequency-modulated system. FM exibits two unique characteristics:

a) A sharp threshold occurs at some value of signal-to-noise, at which point intelligent information may be received. This is commonly referred to as the "FM Improvement Threshold". This improvement of FM over AM signal-to-noise is dependent upon the FM modulation index. In an AM system the receiver output signal-to-noise ratio is approximately the same as the carrier signal-to-noise ratio. The curve in Figure 3 shows the relationship between carrier-to-noise ratio(C/N) required for a desired receiver signal-to-noise ratio(S/N) for various FM modulation indexes. For television transmission the quality of the picture is a function of the receiver output signal-to-noise ratio. Considerable power savings may be obtained using frequency modulation feed back (FMFB) and phase lock loops (PLL) techniques in the receiver circuitry. These techniques in a sense improve the conventional FM threshold level. The actual power saving, or amount of improvement, is dependent upon the design of the system; i.e., desired receiver signal-to-noise ratio, I.F. bandwidth modulation index, etc.

b) If the signal-to-noise ratio does not exceed this threshold level, no usable information or intelligence can be received.

3.0 MALFUNCTION OF ELECTRICAL OR MECHANICAL EQUIPMENT AND ITS EFFECT ON THE COMMUNICATIONS LINK

The overall communications link is composed of the transmitter and receiver loop. A general block diagram of each of these loops, as they apply to lunar station (MOLAB) is shown in Figure 3.

The purpose of the components will be explained and each will be examined to determine how a malfunction will effect the system.

3.1 MODULATOR

The modulator serves the function of impressing the information obtained from the telemetry equipment on the carrier frequency of of the RF transmitter. This information may be contained in the form of a composite signal, which is composed of a number of sub-carrier frequencies, determined by the number of channels. These, in turn, have been modulated by a signal which is proportional to the measured information.

The modulator varies either the amplitude, frequency, or phase (or some combination) of the RF carrier with the amount of this variation dictated by the composite signal. The method in which this is done is determined by the type of modulation used (amplitude, modulation, frequency modulation, or phase modulation).

Modulators basically are composed of electronic devices used to vary the voltage of an oscillator, which is generating the carrier frequency. Should a malfunction occur in this circuitry, effecting the operation of the modulator, the transmitted information would become distorted or unusable. It would, therefore, be desirable to provide a redundant modulator system.

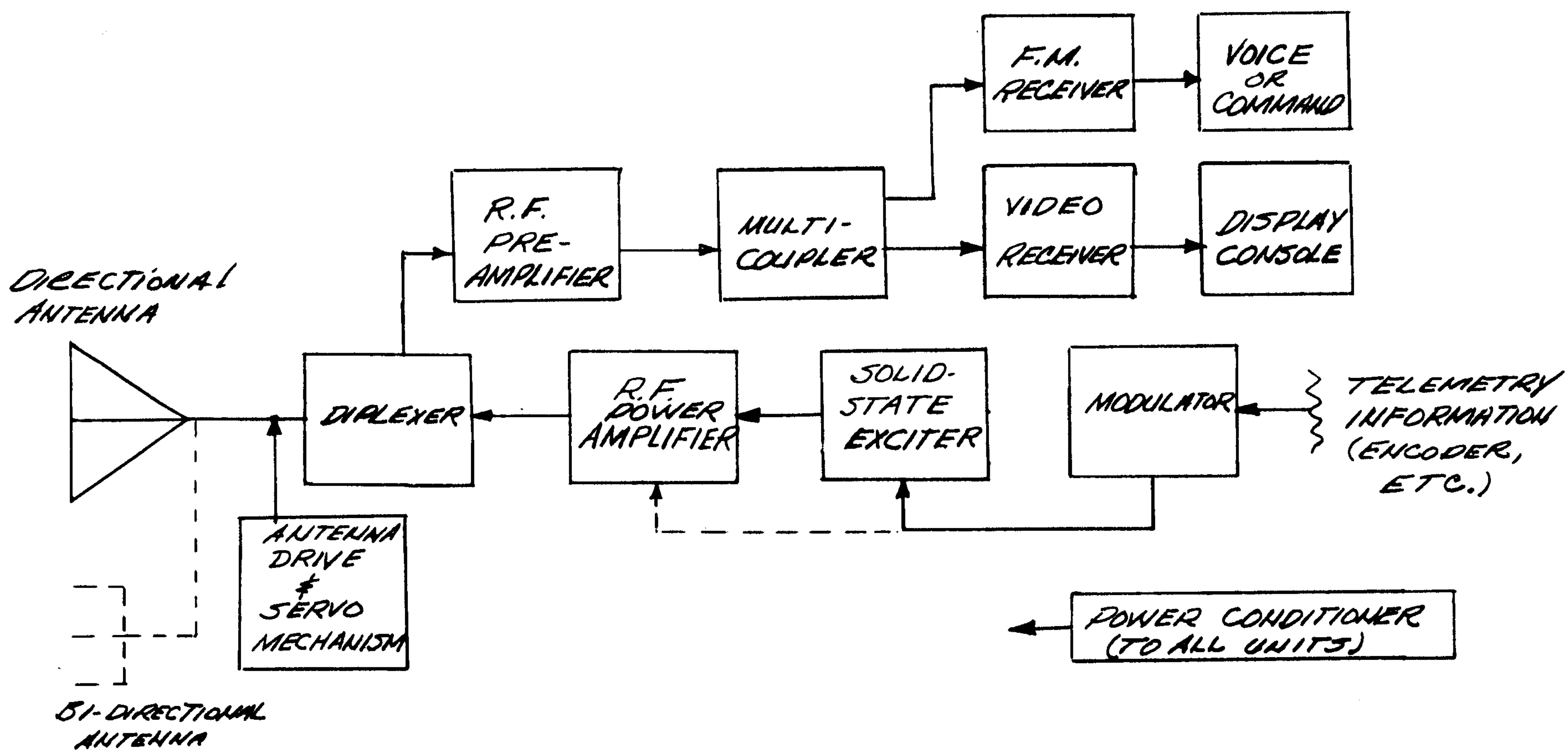


FIGURE 4. TRANSMITTER AND RECEIVER GENERALIZED BLOCK DIAGRAM

3.2 EXCITER

The exciter is a piece of equipment that converts the primary power, usually a d.c. source, into electro-magnetic energy at the desired frequency for transmission, i.e., the carrier frequency. There are a multitude of methods by which this conversion may be accomplished. The method to be considered for the MOLAB operation will probably be a solid-state PM or FM exciter, due to the low mass achievable with Micro-Electronic circuitry and FM modulation providing a more economic utilization of power compared to an AM system.

This device is basically a series of voltage-controlled oscillators (VCO) and frequency multipliers. The desired carrier frequency is generated by multiplying the basic frequency of oscillation of the various oscillators. It is necessary that the phase or frequency, of these oscillators be extremely stable, as frequency modulation is accomplished by varying the phase or oscillating frequency at a rate proportional to the desired modulating signal.

A malfunction in the exciter circuitry would possibly produce an intolerable drift of the oscillators or a complete loss of the carrier medium. Therefore, due to the importance of the device, a redundant exciter is considered a necessity for a reliable communications link.

The state-of-the-art RF power output of the solid-state exciter, at the frequency band of interest (2300 mcps), is limited to approximately one watt. This level may be increased two to three watts within a few years by advancements in the art.

3.3 RF POWER AMPLIFIER

The RF power amplifier is, as the name implies, a device to amplify the RF power output of the solid-state exciter. The amount of amplification or gain is dependent on the system design. Typical values for the RF power necessary for the MOLAB link are 20-50 watts. State-of-the-art power amplifiers such as traveling-wave tubes (TWT), backward-wave amplifiers (Amplitrons), and planar triodes, will provide 20 to 30 db gain over the input signal.

It is essential for the power amplifier to faithfully reproduce the input signal in such a way that the modulation impressed on this signal will not be distorted. Therefore, the amplifier should be a low-noise, distortion-free, linear device. A desirable feature of the RF amplifier would be the ability to pass the low-level RF signal (exciter output) without noise or distortion should a malfunction occur in the amplifier. Tubes such as the Amplitron have this feature. A slight amount of attenuation (approximately 0.5 db), which is due to the physical parameters of the tube, is the only effect produced on the low-level signal.

The communication link should be designed so that the low-level transmitter power will be sufficient to transmit a minimum (voice link) bandwidth of 2.5 kc to the earth in the event that a malfunction should occur in the RF power amplifier. Conditions permitting, a redundant RF power amplifier would be a desirable feature of the communication link.

3.4 DIPLEXER

The diplexer allows a single antenna system to be used for simultaneous transmission and reception on two slightly different frequencies. It should have high isolation between the transmit and receive ports, low VSWR, low insertion loss in the pass band, and should be broad band.

This device requires no electrical power, and the parameters are physically fixed by the design. Thus, the reliability is high, and the possibility of a malfunction occuring is extremely low.

3.5 ANTENNA AND POSITIONING SYSTEM

The antenna system is the "end" device necessary to transmit or receive the desired information. The physical and electrical characteristics of the antenna system are dependent upon the link parameters, i.e., RF power output, information bandwidth, frequency band of operation, and degree of positioning required by the MOLAB mode of operation.

A typical antenna system, suitable for the MOLAB, will be described as to method of operation and effects of malfunction.

Consider an antenna system for the frequency band of 2300 megacycles. A directional antenna of approximately 20 db gain is necessary in order to obtain the most effective use from the RF power available. An optimum, or "trade off" design, is necessary between antenna parameters (gain and mass) and transmitter parameters (power input, power output, and mass), in order to make the most advantageous use of the mass and power allocated for the MOLAB communications link. Refer to section 6.0 for this study.

It is <u>essential</u> that the directional antenna be automatically positioned in such a way that information may be transmitted from and commands may be received by the MOLAB during the unmanned mode. Since it would not be feasible, from a mass and space standpoint, to have a totally redundant antenna system, it is necessary that the reliability of the antenna and drive system be maximized. This may be accomplished by stringent evaluation under simulated lunar environment of such parameters as, lubrication materials, gear boxes, positioning servos, etc., of the drive system.

A possible means of positioning the directional antenna to assure that it will always point toward the earth would be through the use of an electromechanical drive system. Requirements for this type of system include: the directional antenna with a low gain (0db) antenna attached, lobe switching circuitry, a beacon signal from the earth, and a servo-loop to the electro-mechanical drive.

Initial acquistion would be accomplished by commands from earth received through the omni-directional antenna. These commands would energize the directional search mode. Through the use of the beacon signal, transmitted from earth, a voltage would be generated in the servo-drive loop. A maximum voltage,maximum field strengh of the beacon signal, would bore sight or position the directional antenna at the earth.

In the dormant mode of the MOLAB, the antenna would be locked in this bore-sighted position and would be capable of transmitting and receiving the desired information. Both the unmanned and manned roving modes of the MOLAB will require the antenna system to continuously track the earth. Although it is desirable to have a high reliability factor on the antenna and positioning system, it is possible that a malfunction could occur.

It would be desirable for the communications link to be designed in such a way that the minimum bandwidth (2.5 kc.) could be transmitted by using the omni-directional antenna. This would supply a "semi-redundant" antenna system in the event a malfunction should render the positioning system or directional antenna inoperable.

Since it is required that the antenna system be external of the MOLAB vehicle, the effects of meteorite bombardment should be considered.

Accurate data regarding size, frequency, and density of meteorite bombardment is not available. This information will not be known until actual data has been taken on the lunar surface by projects such as Surveyor, etc.

Small particles striking the antenna system (assuming a parabolic reflector is used), may erode, dent, or puncture this surface. Minor surface damage will not appreciably degrade the antenna performance. An exception to this would be the destruction of the feed antenna; the system in this case would be reduced to the omni-directional antenna or narrow band-width mode of operation. Total destruction of the antenna system would, of course, terminate communications.

The antenna, being external of the MOLAB, also presents another problem area: that of physical antenna deformation due to its exposure in the extreme lunar environments. A study to determine the extent to which deformation of the antenna will degrade the antenna design characteristics is necessary. A study of this nature would entail an analysis of usable antenna configurations, possible fabrication materials, the effects of non-uniform temperature differentials on these materials, manufacturing processes used in the antenna fabrication, and the applicable environmental conditions.

3.6 RECEIVING LINK

The preceding analysis is applicable to the transmitter link of the MOLAB. It now is necessary to make a similar study of the receiving system for the MOLAB vehicle.

The antenna, antenna positioner, and diplexer have been described. These components are common to the transmit and receive system.

Although state-of-the-art techniques should be utilized in the MOLAB receiving system design, the prime objectives should be low mass low power drain, and high reliability. The transmitter capability of the earth-based ground station.(DSIF) is more than adequate to supply a resonable level of signal at the lunar station (MOLAB).

3.7 RF PRE-AMPLIFIER

A pre-amplifier is used to amplify the signal received by the antenna. It also performs the functions of rejecting unwanted signals occuring outside the desired R.F. spectrum.

The pre-amplifier must be capable of amplifying the received signal without contributing any additional noise or distorting the signal. The major source of noise at the lunar station will be that associated with cosmic and solar activity.

The location of the antenna, with respect to thermal radiating apparatus, i.e., MOLAB radiator, also will contribute to the thermal noise level. This effect (radiator heat) will be more pronounced in the lunar day operation, and also will be a function of the temperature of the radiator.

It will be necessary, therefore, for the RF pre-amplifier to have sufficient amplification such that information may be received during these periods of high noise, if continuious communications are to exist with the earth.

3.8 MULTI-COUPLER

Multi-couplers are used in the receiving system when it is necessary to connect several receivers to a single antenna for the purpose of simultaneously receiving more than one channel of information in the same frequency band.

A multi-coupler consists of a combination of amplifiers and isolation networks. Malfunction of the multi-coupler possibly could produce cross-talk between channels, due to poor isolation. Distortion of the received information may occur if the amplifier should operate in a non-linear condition.

3.9 RECEIVERS

The actual equipment which is used to remove intelligence from the carrier and convert it to a usuable quantity is called the receiver. the type of receiver, AM, FM, etc, is determined by the method of modulation chosen to transmit the desired information. The information then is utilized in the form of voice, command functions, or TV display, by means of the appropriate end instrument.

Three basic types of information will be transmitted from earth to the MOLAB vehicle:

a) Command Information - This will perform necessary functions of equipment control (on and off), antenna positioning, locomotion, etc. The requirement for earth command will exist, to some degree, in all modes of the MOLAB operation: dormant, unmanned roving, and manned roving.

b) Voice Communication - In the manned mode of operation the MOLAB vehicle will require continuous voice contact from earth and from the orbiting command module during the portion of the orbit when it is in range.

c) Television Communication - The MOLAB vehicle may have the ability to receive and display television communications from the earth. The purpose of this television channel could be to aid the astronaut in the repair of an identical piece of equipment on earth or in conducting scientific experiments. Therefore, the extent of time that this TV channel will be utilized will be determined by the necessity for this type of earth assistance.

It would be highly difficult to analyze the various types of malfunctions which may occur in the receiving system. Since the reception of voice and command functions are of prime importance to the proper operation of the MOLAB, it would be desirable to provide a redundant system for this information.

4.0 MOLAB S-BAND EFFECTIVE RADIATED POWER REQUIREMENT

The effective radiated power required to communicate between the moon (MOLAB) and the earth is dependent, primarily, upon three variables:

a) RF base bandwidth required (B)

b) Cabrier-to-noise ratio (S/N)

c) Effective noise temperature (T_E)

This is shown by the analysis of the RF link equation below:

$$ERP = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{kT_E \; B \; S/N \; L}{G_R}$$

where ERP is equivalent to the power output of the transmitting antenna.

Rewriting the above expression in db or logarithmic form:

$$ERP_{(dbw)} = 20\log\left(\frac{4\pi R}{\lambda}\right)^2 + 10\log k + 10\log T_E + 10\log B + 10\log S/N + 10\log(L) - 10\log G_R$$

The fixed parameters of the system are:

a) Space attenuation, 20 log $\frac{4\pi R}{\lambda}$, where R is distance to the moon, 387 x 10^6 meters; and λ is the wavelength at 2300 mcps or 0.13 meters.

b) 10 log k, where k is Boltzmann's constant or 1.38 x 10^{-23} joules per degree Kelvin.

c) Losses and safety factor designed into the system, 10 log L = 6 db.

d) Gain of the receiving antenna, G_R, taken as the DSIF 53 db gain antenna.

Thus the expression may be written:

$$ERP_{dbw} = 211.4 - 228.6 + 6 - 53 - 10 \log T_E + 10 \log B + 10 \log S/N$$

$$ERP_{dbw} = 10 \log T_E + 10 \log B + 10 \log S/N - 64.2$$

The effective noise temperature will be assumed to have a fixed value of 271°K (system noise temperature reported by JPL of 71.7°K and moon brightness temperature of 200°K). This will be approximately true, except during periods of cosmic disturbances. Therefore:

$$ERP_{dbw} = 10 \log B + 10 \log S/N - 40$$

A typical requirement for the MOLAB, based on the TV communication link, might be a base bandwidth (B) of 1.0 megacycles per second and a carrier-to-noise level of 16 db. It is seen that with these parameters, an ERP of approximately 36 dbw (4×10^3 watts) is required to communicate with the earth.

Figure 5 is a family of curves obtained from the above expression for ERP. This plot expresses the required ERP for a desired carrier-to-noise ratio and bandwidth.

If an FM modulation index of 2 is used, the 1 mcps base bandwidth has associated with it an R.F. bandwidth of approximately 5.5 mcps, as shown in Figure 6. This is well within the capability of DSIF and MSFN, which have a 10 mc R.F. bandwidth.

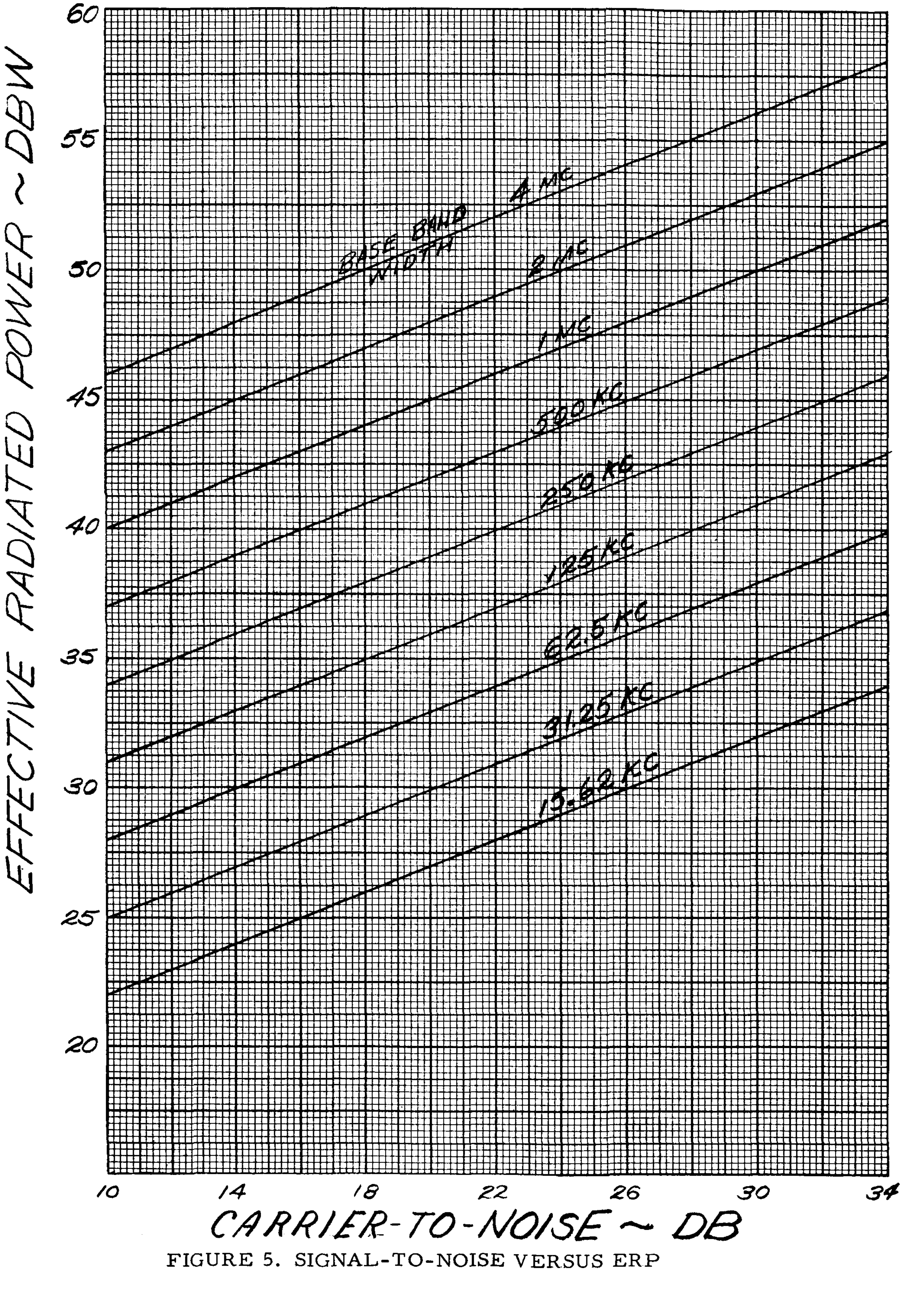


FIGURE 5. SIGNAL-TO-NOISE VERSUS ERP

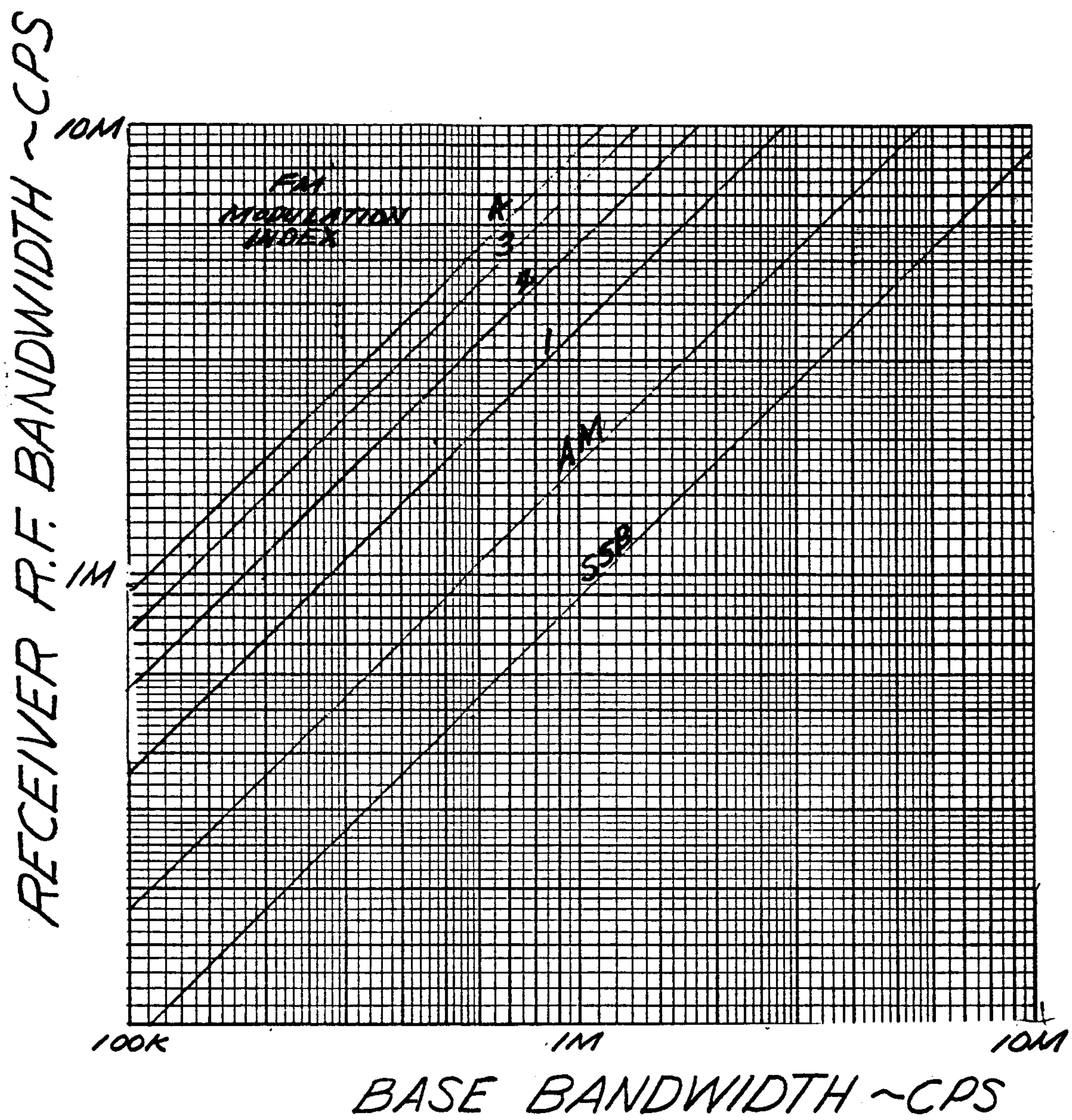


FIGURE 6. RECEIVER R. F. BANDWIDTH VERSUS BASE BANDWIDTH

5.0 STATE-OF-THE-ART OF VARIOUS RF TRANSMITTERS AND POWER AMPLIFIERS

This section will be primarily of an informative nature and will include only transmitters and power amplifiers that are applicable to MOLAB installation and operating frequency band. The frequency band, 2100 to 2300 mc, is of the utmost importance, although equipment at 960 mc and 1705 mc will be considered.

Since a considerable amount of the state-of-the-art information on the described equipment is of a classified nature (either National Defense or Company Proprietary), the information contained in this report will consist of advertised equipment.

5.1 GENERAL

A discussion of the various types of microwave devices available is necessary. In order to analyse and determine the compatibility of these devices with the MOLAB system, the following parameters should be considered:

a) RF Transmitters or Exciters

1) Frequency band - stability, drift
2) Method of modulation - AM,PM,FM, etc.
3) Bandwidth
4) Power input - d.c.
5) Power output - RF
6) Overall efficiency

7) Environmental characteristics - vibration, shock acceleration, thermal, etc.

8) Reliability effects - MTBF (mean time before failure)

9) Radiation effects

10) Cooling requirements

11) Noise figure

12) RFI

13) Physical characteristics - size and mass

b) Power Amplifiers

1) Operating frequency

2) Bandwidth 3 db

3) Input power - d.c.

4) RF exciter power

5) RF output power or gain

6) Noise figure

7) Reliability - MTBF

8) Environmental characteristics

9) Radiation effects

10) RFI

11) Cooling

12) Physical characteristics - size and mass

13) Effects of malfunction

Several types of microwave tubes are adaptable for the MOLAB communication system. These are:

a) Transmitters or Exciters
   1) Solid-State Transmitters
   2) Microwave Triodes (Planar Triodes)
   3) Voltage Tunable Magnetrons (VTM)
   4) Backward-Wave Oscillators
   5) Stabilitrons

b) RF Power Amplifiers
   1) Traveling-Wave Amplifiers (TWA)
   2) Microwave Triodes (Planar) (Cavity Amps)
   3) Backward-Wave Amplifiers (Amplitrons)
   4) Klystron Amplifiers

5.2 TRANSMITTERS OR EXCITERS

The terms transmitter and exciter are used loosely in communication terminology.

The transmitter is that system of equipment which supplies the RF power to the antenna for transmission purposes.

The exciter usually is considered that portion of the transmitter which generates the transmitter output frequency and raises it to a power level suitable for exciting the RF power amplifier stages. It basically is composed of an oscillator, which supplies the source from which the carrier frequency is obtained, and the frequency multipliers or converters, used to increase the frequency of the oscillator to the desired carrier frequency. Modulators and low level RF amplifiers usually are considered a part of the exciter equipment.

Solid-state exciters are, as the name implies, exciters whose circuitry consists of solid-state devices such as silicon semiconductors, capacitors, varactors, etc.).

The state-of-the-art RF power output of solid-state exciters at S-Band frequencies (2300 mc) seems to be limited to less than one watt (750 mw). Although this is a low RF power level, it is adequate to excite most RF power amplifiers. The RF power output of these devices is expected to increase to 3 to 5 watts within a few years, as present state-of-the-art techniques are improved.

The modulation bandwidths of the S-Band solid-state exciters investigated range from d.c.to 6.0 mcps. This bandwidth capability is a function of equipment design and adheres to the limits specified by IRIG standards. Thus, the state-of-the-art is not reflected in this parameter.

The bandwidth requirement necessarily will be a function of the type of modulation utilized and the amount of information to be transmitted.

All information indicates that the modulation bandwidths for solid-state exciters are adequate for the MOLAB requirements.

The physical size and mass of solid-state exciters, including power supply and modulation circuitry, varies slightly in the power range of 0.25 to 1.0 watts. The average values are approximately 1300 to 1640 cm^3 (80 to 100 cu. in.) of volume and 0.91 kg (2 lbs.) of mass. The efficiency of these devices, relative to RF output versus d.c. input, is approximately 2 to 5 percent.

MTBF tests on various exciters indicate that the life of operation is more than 8000 hours, which should be adequate for MOLAB operation and pre-launch checkout.

5.3 PLANAR TRIODE TUBES

Planar triodes are microwave oscillator tubes which make very good microwave transmitters (exciters of RF amplifiers), when provided with the necessary circuitry.

The use of ceramic-metal construction makes this type of tube a rugged and reliable device for deep space application. RF output powers of approximately 40 watts at 1000 mc and 18 watts at 2500 mc are obtainable by utilizing these triodes as oscillators. These devices may be modulated, by appropriate circuitry, to produce AM, FM, PM, etc., modulation.

Bandwidth (3db) of operation, when used as an amplifier, is approximately one percent of center frequency. RF power gain is between 10 and 12 db over low level exciter input. The RF power output, therefore, is a function of the exciter power and amplifier design. At S-Band frequencies 20 watts seems to be the limit of operation for a lightweight, conduction-cooled amplifier design using triodes. Power efficiencies of 20 to 25 percent are achieved easily by using ceramic-metal planar triodes in cavity amplifiers. The physical size and weight of a typical amplifier unit are: 490 cm^3 (30 cu. in.) of volume and 0.68 to 0.91 kg (1.5 to 2.0 lbs.) of mass.

5.4 CROSSED-FIELD TUBES

Voltage tunable magnetrons (VTM) are CW oscillators used in the microwave frequency bands. Essentially, the VTM is a crossed-field tube (or M-Type tube) of low Q, which allows it to be tuned or modulated by changes in the anode voltage. The VTM differs from the ordinary magnetron, which also is a crossed-field tube, but which has a high Q and requires physical variations of the resonant cavity (mechanical tuning) to vary the frequency of oscillation.

The actual method or theory of operation of the VTM is not pertinent to this report, although this information may be obtained in the reference text. However, a few of the major characteristics of the VTM will be mentioned.

The methods of modulating a VTM are limited to amplitude and frequency modulation. The VTM is one of the easiest devices to frequency-modulate. Theoretically, the VTM may be frequency-modulated up to the frequency of oscillation, but practical application (tube reactances) limits the frequency of modulation to approximately 50 mc. FM is accomplished by varying the anode voltage, since the frequency of oscillation is a linear function of anode voltage. This FM is accomplished by using techniques employed to amplitude-modulate a class "C" amplifier, such as utilizing a series modulated transformer, and series resistor modulation, etc.

The VTM may be amplitude-modulated to some degree. AM is produced in the VTM by varying the voltage to the injection electrode, which controls the power output of the VTM. If the voltage to this electrode is decreased to a value insufficient to bunch the incoming electrons, the VTM will drop out of oscillation. Therefore, the tube cannot be used for 100 percent AM service. The actual percentage of modulation is a function of the specific tube design.

Power output of the VTM begins at a few milliwatts and, theoretically, can be extended to hundreds of watts. Present state-of-the-art limits this output to less than 10 watts at S-Band frequencies.

Typically, the VTM is capable of satisfactory operation in relatively severe environmental conditions of altitude, vacuum, shock vibration, acceleration, etc. Tests have been performed which indicate that repeated exposure to gamma intensities as high as 1.68×10^7 rad/s and neutron intensities as high as 2.66×10^8 rad/s does not alter the tube performance. Thermal environments for operation are -55°C to +125°C. Physical characteristics for an S-Band VTM are approximately 1480 cm^3 (90 cu. in.) and 2.27 kg (5 lbs.), excluding power supply and modulation circuitry.

5.5 BACKWARD-WAVE OSCILLATORS (BWO)

The backward-wave tube is another microwave device suitable for use as a voltage-tunable oscillator (exciter) or as an RF amplifier.

Basically, these tubes may be of the M type or the O type. This denotation describes the orientation of the electron beam to the magnetic field; the O type referring to tubes in which the electron beam flows parallel to the magnetic field and the M type referring to tubes in which the electron beam flows normal to the mutually perpendicular d.c. magnetic field. The M types also are called crossed-field tubes.

O-type BWO's are generally of low efficiency: one to five percent. State-of-the art developments regarding this type of tube are primarily in the area of signal sources in the millimeter wave region (100 Gc or greater).

M-type BWO's are suitable oscillators at S-Band frequencies. The efficiency of these tubes theoretically may be as high as 80 percent, but in practice efficiencies of 20 to 50 percent are obtainable. These tubes have a relatively high power (1 kw at 3 kmc) and are voltage tunable; the frequency of oscillation is a linear function of the beam voltage. FM is obtained by varying the beam voltage; AM can be obtained by varying the beam current.

5.6 BACKWARD-WAVE AMPLIFIERS

In general, the crossed-field tubes are classified in two groups: reentrant-beam tubes and non-reentrant-beam tubes. Reentrant-beam tubes may use either a backward-wave or a forward-wave circuit structure.

Although both classifications mentioned may be used, the type most applicable to the MOLAB is the reentrant-beam tube of the backward-wave circuit structure. This tube usually is classified, by its Raytheon trademark, as an Amplitron. These tubes act as locked oscillators and have a reported operational efficiency (d.c. power input to RF power output) of 50 to 60 percent. In some cases, for low-gain Amplitrons, 80 percent efficiencies are obtainable. This relatively high efficiency is the primary electrical advantage of the backward-wave reentrant-beam tube over other power amplifier tubes.

Certain RF gain and bandwidth restrictions are imposed on the Amplitron type of tubes. These restrictions result from the short drift space between input and output, which is necessary to produce a strong positive electronic feedback. The bandwidth of this type of reentrant-beam tube with short drift space is normally less than eight percent of the center frequency with a corresponding RF gain of approximately 10 to 12 db. Gains of up to 20 db for low output power tubes (10 watts) have been reported.

The Amplitron is basically a simple structure, consisting mainly of coaxial cavity resonators and transmission lines. This type of tube possesses certain inherent characteristics which make it an ideal tube when used as the power amplifier stage in an RF system.

Most important is the "Fail Safe" mode of operation. In most power amplifiers (klystrons, traveling-wave amplifiers, etc.) a malfunction or failure usually results in distortion or complete loss of output power. Failure or loss of input power to the Amplitron will result in a loss of amplification but the RF drive power will appear at the output terminals of the Amplitron. This RF drive power will be attenuated slightly (0.5 db) due to insertion loss of the tube, which is acting as a series section of a coaxial line. Thus, limited communications still could exist.

RF power output of the Amplitron is primarily a function of the anode current (it uses a regulated current supply), and the internal magnetic field strength. As long as sufficient RF drive (exciter) power is applied to the tube, amplification will result. If insufficient drive is applied, the tube will oscillate. This should not be a problem area, however, as 100 mw is sufficient to drive most tubes.

The RF drive power does not require regulation in the Amplitron, as tube gain is a function of anode current and magnetic field. Therefore, variations in the drive power output (input to amplifier) are not amplified but appear at the output of the amplifier as a 1:1 ratio.

Multiple levels of power output may be obtained by staging several power amplifiers. Beam power switching of the various Amplitrons would result in the desired RF power output. The estimated MTBF of the Amplitron is in excess of 10,000 hours. Values of 33,000 hours are reported for these tubes. Tests have been performed over a $-40^{o}C$ to $+80^{o}C$ temperature range and within the standard space environmental characteristics (vibration, shock, vacuum, etc.) with very little tube degradation.

Typical physical characteristics for the Amplitron tubes are 0.91 to 1.36 kg (2 to 3 lbs.) and 820 cm^3 (50 cu. in.), excluding power supply.

5.7 KLYSTRON AMPLIFIERS

The klystron type of tube is dependent on transit-time effects for efficient operation. A cavity resonator is used in such a way that a small amount of drive power will produce a high a.c. voltage across the cavity gap. The resulting velocity modulation and bunching action produces a large a.c. current in the beam. The output cavity is located at a fixed distance from the resonator cavity and the high voltage induced across the grid of the output cavity is coupled to the tube output to produce amplification. Increased amplification and efficiency result when one or more tuned cavities are placed between the input and output cavities. Typically, four cavities are used to produce approximately 30 db saturated gain (S-Band tubes). Tube bandwidth, as well as power gain, is a function of the number of tuned cavities. Typical bandwidths are 0.25 percent of center frequency. Overall efficiency of the klystron amplifier is about 30 to 35 percent.

Either the magnetic or the electro-static method may be used to focus the electron beam. Tubes using magnetic focusing (either permanent magnets or electro-magnets) have an advantage of higher efficiency but are heavy and bulky. The use of electro-static (periodic magnetic) focusing provides a lighter-weight system. This method of focusing, as applied to the klystron, is presently in the developmental stage. Suitable tubes, using electro-static focusing, should be avaliable within a few years (1967-1969). The typical mass of an S-Band tube capable of 200 watts RF output (25 db gain) will be approximately 0.91 kg (2 lbs.), excluding the power supply.

Environmental characteristics of the electro-static focused klystrons should be similar to those of other microwave tubes designed for space application.

possible to design cathodes with an expected life of 100,00 hours or greater.

5.8 TRAVELING-WAVE AMPLIFIERS

The traveling-wave amplifier is similar in operation to the klystron. Instead of the tuned cavities, the TWA uses a helical slow-wave structure. The main advantage of the traveling-wave amplifier is the ability to provide high gain over a wide bandwidth. Greater-than-octave bandwidths are possible with high gain (30 db) tubes. Typical S-Band traveling-wave amplifiers provide 30 to 40 db saturated gain with d.c. to Rf conversion efficiencies of approximately 30 percent.

Beam focusing may be achieved by using the same methods discussed for the klystron; i.e., permanent magnet, electro-magnet, or electro-static (periodic permanent magnet, PPM). The PPM method of beam focusing is well within the state-of-the-art for traveling-wave amplifiers. TWA's with PPM focusing are presently used on satellites, such as Synocom and Telstar, with a high degree of sucess and reliability. These tubes are very light in mass; a 20 watt tube having a weight of approximately 0.36 kg (0.8 lbs.) including the PPM system but excluding the necessary power supply. The highest power obtainable with present state-of-the-art techniques in lightweight S-Band PPM-focused TWA tubes is approximately 100 watts with a tube mass of approximately 1.13 kg (2.5 lbs).

RF power output is a non-linear function of the RF drive power input and the beam voltage; therefore, the tube is more readily adapted to an FM or PM system than to an AM system. Maximum efficiency is obtained by using an FM system in order that the tube may be continuously operated at saturation by the RF driver. RF power output drops off slightly if drive power output is increased above the value necessary to produce saturation. This saturated drive power level (typically 0.5 to 10 mw), is a function of the applied beam voltage. The TWA's have good phase characteristics when the beam voltage is regulated; typical phase sensitivity of this voltage is two degrees per volt.

The useful bandwidth is approximately an octave (1000 mc at S-Band), which is many times the bandwidth requirement for MOLAB communication. The inherent wide-band capability is an advantage even in narrow-band applications because it means that operating characteristics are very insensitive to environmental changes and parameter variation is minimized over a modulated signal bandwidth.

State-of-the-art advancements in lightweight PPM traveling-wave amplifiers report a 40 percent beam efficiency (a 36 percent overall efficiency, including heater power). This high efficiency results from an optimum depressed collector design (collector voltage reduced to approximately 50 percent of the helix voltage) and a thermally efficient heater-cathode design.

The mass of a 20 watt TWA suitable for space environment is 0.498 kg (1.1 lbs.) plus approximately 0.91 kg (2 lbs.) for the solid-state d.c.-to-d.c. converter (power supply). The tube and power supply occupy approximately 490 cm^3 (30 cu. in.) of space.

The power output may be set at various levels by appropriate anode voltage changes, i.e., 20 watt and 5 watt modes, although the tube efficiency will be reduced in the lower power mode from 35 to 40 percent to 25 pefcent. The MTBF of TWA's (primarily the cathode life) may vary from 10,000 hours to 100,000 hours depending on the mode of operation and the materials utilized in cathode construction.

6.0 MOLAB S-BAND SYSTEM WEIGHT ANALYSIS

6.1 GENERAL

It is desirable to provide some representation of the RF power output as a function of "system" mass. The system is composed of the equipment necessary to generate the desired RF carrier frequency at a power level of the proper magnitude to be applied to the antenna for transmission; i.e., the system will be composed of the modulator, exciter, stages of power amplifiers, high voltage power supplies, isolator, and band-pass filter.

It may be seen, from the study and description of various types of microwave tubes and exciters, that many methods (different combinations of equipment) can be used to compile the system. However, parameters such as efficiency, mass , reliability, the most effective use of primary power, bandwidth, method of modulation, simplicity of operation, mode of failure, and cost are of prime importance in determining the most practical system.

It has been calculated (see section 4.0) that approximately 36 dbw (4×10^3 watts) of effective radiated power is necessary for the MOLAB S-Band communications link. It is easily seen that power of this magnitude is not feasibly generated by the transmitter alone; thus some directivity (gain) is necessary for the transmitting antenna.

$$ERP = P_x G_A$$

In the above expression, ERP is the total power radiated, or the effective radiated power; P_x is the RF power of the transmitter; and G_A is the gain of the transmitting antenna.

Associated with the above expression are the masses of the transmitter (W_x) and the antenna (W_A). The total mass of the system (W_T) is equal to the summation of these parameters, or

$$W_T = W_x + W_A$$

To obtain an optimum design for the communications link, the total mass of the system is of prime importance. Equally important is the power required and the space occupied by the system.

6.2 TRANSMITTER OUTPUT VERSUS WEIGHT

The most effective type of transmitter for MOLAB use is a system that will supply various levels of RF power to the antenna terminals. This would allow the transmitted power to be a function of the amount of information desired to transmit, thereby making more efficient use of the primary power source.

The use of a solid-state exciter, which utilizes specific combinations of amplifiers and varactor diode frequency multipliers, is preferred to a fixed frequency oscillator, such as a VTM or planar triode exciter. The advantage of a solid-state exciter are:

a) Good frequency stability is obtained by using a low frequency, crystal stabilized VCO.

b) Maximum rejection of unwanted harmonics and minimum susceptibility to RFI is obtained by using appropriated stages of amplification and frequency modulation.

c) A light mass and a small volume may be achieved by using microelectronic circuitry.

A disadvantage of the solid-state exciter is the low electrical efficiency (d.c. to RF), although the total power consumed is low (almost negligible) when compared to the total power consumption of the system.

The desired stages of RF power amplifiers may be used to produce the required RF power level at the antenna terminals.

It is estimated that approximately 600 watts of d.c. power will be available for the S-Band communications system for the MOLAB; thus, with a 30 percent transmitter overall efficiency, about 180 to 200 watts of RF power may be realized.

Various tubes, such as the traveling-wave amplifier, the klystron amplifier, or the Amplitron, are capable of producing gains of 10-30 db above the 0.1 to 1.0 watt output of the solid-state exciter.

The Amplitron-type tube has certain characteristics which make it a desirable power amplifier for the MOLAB operation. These characteristics are the "Fail-Safe" mode of operation, a high efficiency, and the capability of staging several amplifiers in series to produce various levels of RF output power, by energizing the appropriate power supply.

A generalized study of the masses of various complete transmitter systems (exciter, necessary power supplies, power amplifier tubes, circulator, band-pass filter, and cabling) was made for the 0.1 to 200 watt power levels at S-Band (2300 mcps). It was found that for a 200 watt system using solid-state exciters and either a TWA, a klystron, or am Amplitron power amplifier, the total mass will vary between 11.325 and 13.59 kg (25 and 30 lbs.). Data for this power region is represented below:

RF POWER	CONDITIONS	MASS (kg)	EARTH WEIGHT (lbs.)
0.1 watt	Solid-state exciter	0.79	1.75
1.0 watt	Solid-state exciter	3.60	8.0
10.0 watts	0.1 w solid-state exciter, 20 db Amplitron and HV power supply, circulator, & band-pass filter & cabling	5.00	11.0
100 watts	1.0 w solid-state exciter, 20 db Amplitron and Power Supply	8.60	19.0

RF POWER	CONDITIONS	MASS (kg)	EARTH WEIGHT (lbs.)
200 watts	0.1 x solid-state exciter, 20 db Amplitron, plus 13db Amplitron and combined HV power supplies, etc.	12.20	27.0

A curve representing the 10 to 200 watt variation of power versus mass is shown in Figure 7. The plot of the described power levels (10 to 200 watts) produces a straight line, represented by the following expression:

$$P_x = 25W_x - 135$$

6.3 ANTENNA WEIGHT VERSUS GAIN

Since the total system mass (W_T) is composed of transmitter mass (W_x) and antenna system mass (W_A), some analogy of the antenna mass is necessary.

Several types of antenna configurations are adaptable to the S-Band MOLAB system. To obtain maximum compatibility with the ground station (DSIF or Manned Space Flight Network), it is essential that the antenna be circular polarized. An approximate increase in signal of 3 db is

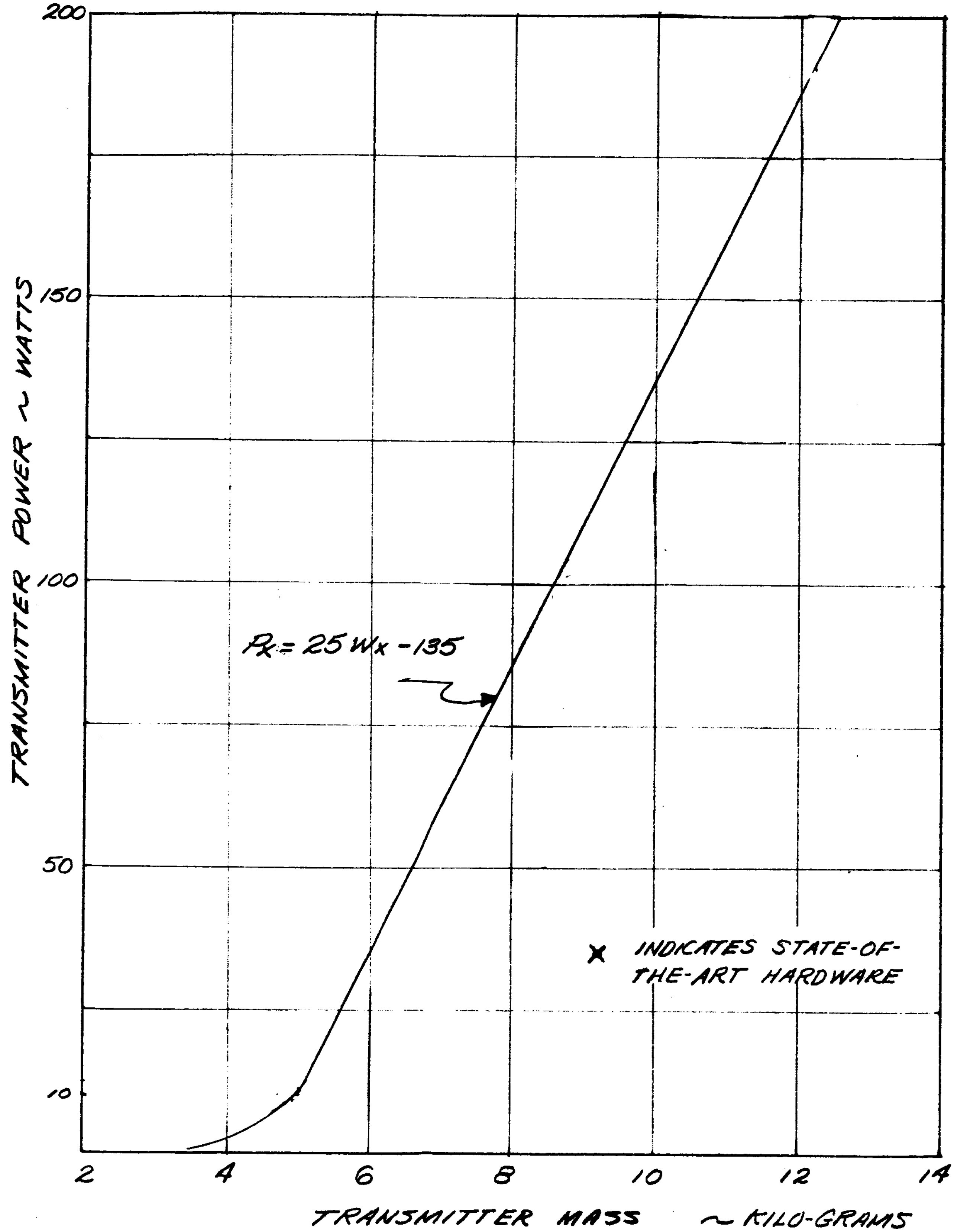


FIGURE 7. TRANSMITTER MASS VERSUS TRANSMITTER POWER

is obtained with a circular-to-circular system as compared to a circular-to-linear system.

Another factor to be considered in selecting the antenna is the relationship between the size, mass, and gain.

Neglecting, for the moment, any trade-off between transmitter power (P_x) and antenna gain (G_A), assume a 36 dbw of effective radiated power (P_T) is necessary for moon-to-earth communications. If we assume P_x to be 20 watts (13 dbw), then G_A would be 23 db.

$$P_T \text{ (in dbw)} = P_x \text{ (in dbw)} + G_A \text{ (in db)}$$

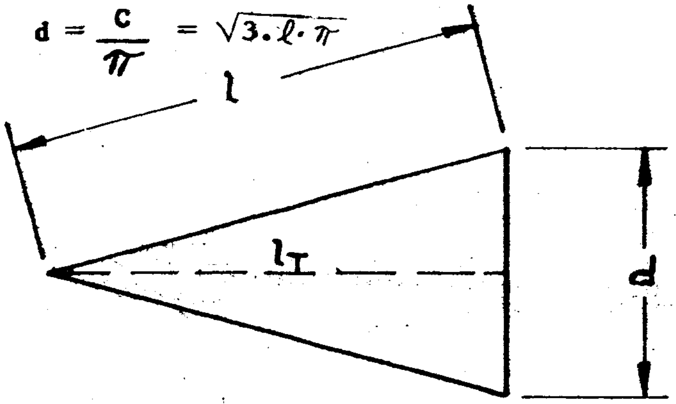
$$G_A = 36 - 13 = 23 \text{ db}$$

Antennas of the parabolic reflector with proper feed, pyramidal or conical horns, and planar slot array can be designed to produce this magnitude of gain with a circular polarized radiation characteristic. Planar slot arrays (crossed-slots for circular polarization) do not seem practical for use at this high a gain due to the complexity, i.e., control of phasing between slot and mechanical tolerances.

A conical horn would lend itself very well to this gain and polarization requirement. The size of an optimum conical horn (maximum aperture efficiency and gain for a maximum phase deviation across the aperture - usually a 3/8 wave-length) may be determined by the following expressions. Where C is the aperture circumference, ℓ is the flare or slant length, d is the aperture diamater, and λ is the wavelength of design frequency.

Gain in db = 20 log $\frac{C}{\lambda} - 2.82$

$$d = \frac{C}{\pi} = \sqrt{3 \cdot \ell \cdot \lambda}$$



A 23 db gain optimum conical horn at 2300 mcps (= 0.13 meters) would be:

$$23 + 2.82 = 20 \log \frac{C}{\lambda}$$

$$1.3 = \log \frac{C}{\lambda} = \log \frac{C}{0.13}$$

$$C = 20\,(.13) = 2.6 \text{ meters}$$

$$d = \frac{C}{\pi} = \frac{2.6}{3.14} = 0.83 \text{ meters}$$

$$\ell = \frac{d^2}{3\lambda} = \frac{.69}{.39} = 1.77 \text{ meters}$$

The actual physical length of the optimum conical horn for this gain figure (32 db), excluding the device necessary to provide circular polarization, is calculated below.

$$\ell_T = \sqrt{\ell^2 + \frac{d^2}{4}}$$

$$\ell_T = \sqrt{(1.77)^2 + \frac{(0.83)^2}{4}} = 1.82 \text{ meters}$$

Therefore, it is seen that a conical horn (due to its length) is not a practical antenna for this gain requirement and for application to the MOLAB.

The next antenna type to be considered is a parabolic reflector and feed antenna. This type of antenna is primarily a parabolic reflector with a feed antenna located at the focus. The design parameters for this type of antenna are functions of many varibles; i.e., the changing of one of the variables effects the others. The most important of these variables, for a maximum gain design, are the ratio of focal length to reflector diameter (F/D ratio), the type of reflector illumination provided by the feed antenna and the choice of feed for minimum aperture blocking.

Typical design values for maximum gain or directivity are an F/D ratio of 0.3, and a reflector illuminated in such a way that the field at the reflector edges is approximately 10 db below that at the center, i.e., the reflector edge is illuminated by the - 10 db point of the feed antenna radiation pattern.

The feed antenna design may be a waveguide horn, a dipole with splash-plate (crossed-dipoles for circular polarization), or some other configuration which will produce the desired primary radiation pattern. The dipole feed seems to be the most practical design for MOLAB use, as it may be supported adequately at the center of the reflector, thus producing minimum aperture blocking.

The gain of a parabolic reflector is a function of the physical aperture area $\left(\frac{\pi D^2}{4}\right)$; the frequency of operation, which determines the space attenuation between the feed and reflector $\left(\frac{4\pi}{\lambda^2}\right)$; and the aperture efficiency. The aperture efficiency is the ratio of the directivity of the parabolic reflector antenna to the directivity of a uniformly illuminated aperture of the same area. Mathematically, this ratio or aperture efficiency may be as high as 78 percent, but experimental results indicate 65 percent to be the maximum, with 60 percent being easily achieved with good feed antenna design techniques. Therefore, the gain of a parabolic reflector is:

$$G_A = (\text{EFF. \%})\ (\text{AREA})\ \frac{4\pi}{\lambda^2}$$

$$= (0.6)\ \left(\frac{\pi D^2}{4}\right)\ \left(\frac{4\pi}{\lambda^2}\right) = \frac{0.6\pi^2\ D^2}{\lambda^2}$$

at 2300 mcps, $\lambda = 0.13$ meters

$$G_A = 3.5 \times 10^2\ D^2 \quad (\text{D in meters})$$

$$G_{A\ (db)} = 10 \log 350\ D^2$$

Thus, for a 32 db gain parabolic antenna, @ 2300 mc, the diameter would be:

$$G_{A\ (db)} = 10 \log 3.5 + 10 \log^2 + 20 \log D$$

$$GA = 25.42 + 20 \log D$$

$$.23 - 25.42 = 20 \log D$$

$$-0.12 = \log D; \text{ or } 0.12 = \log \frac{1}{D}$$

$$D = 0.76 \text{ meters}$$

The depth of the antenna for a F/D ratio of 0.3 would be approximately 0.23 meters.

Therefore, of the three types of antennas described, the parabolic reflector and feed seems to be the most practical type when a high gain is desired.

Figure 8 is a plot showing the relationship of gain versus the diameter for the parabolic reflector, with noted parameters of frequency, illumination, and aperture efficiency.

It now is desirable to formulate some expression for the total mass of the antenna system (W_A) as a function of the antenna size, i.e., the diameter (D) of the reflector. The mass of the reflector, the feed antenna, all necessary structural supports, and the drive mechanism will be included in the overall mass of the antenna. An analysis of these various antenna components as a function of antenna diameter is to be determined. Figure 9 is a drawing of the parabolic reflector to be examined.

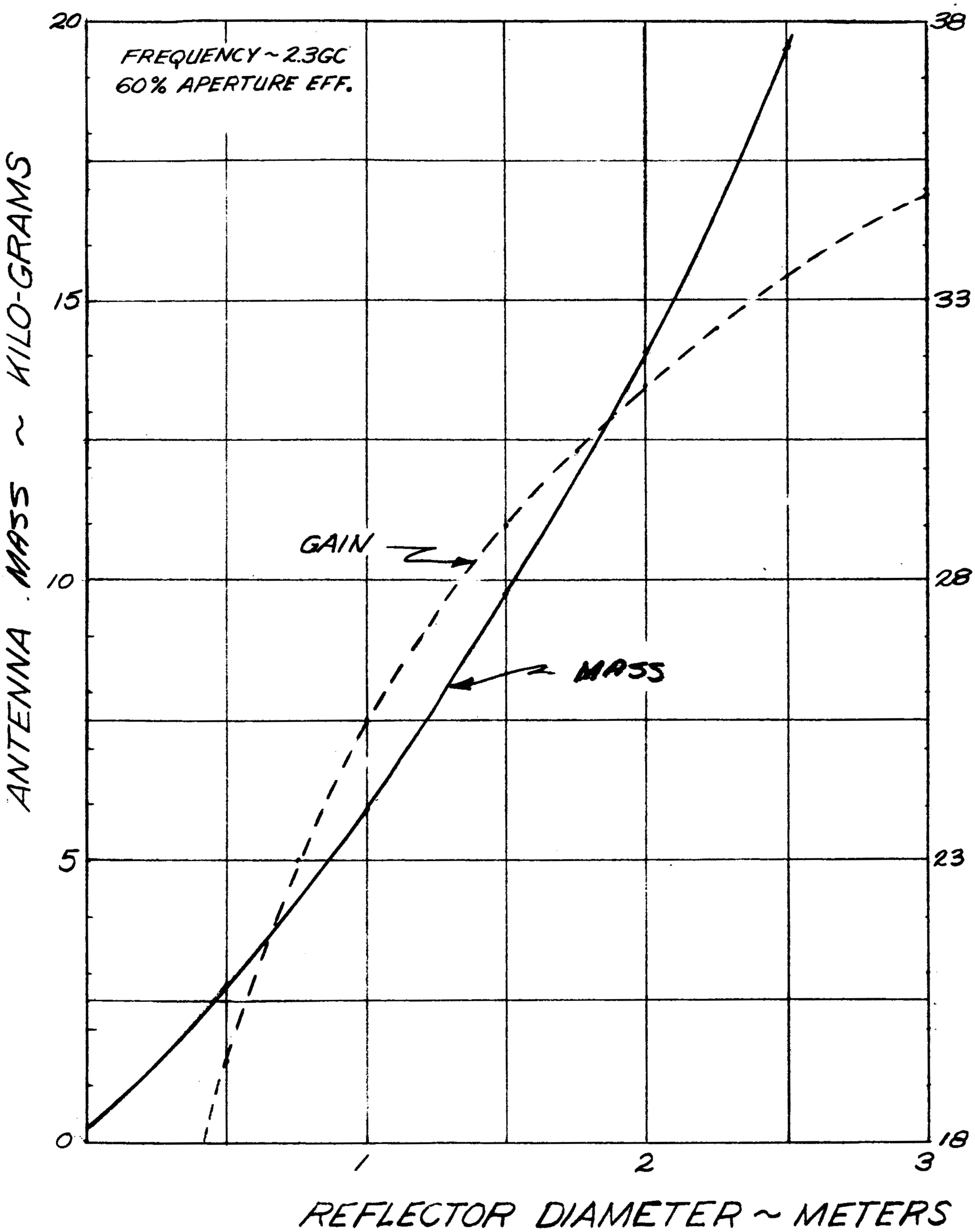
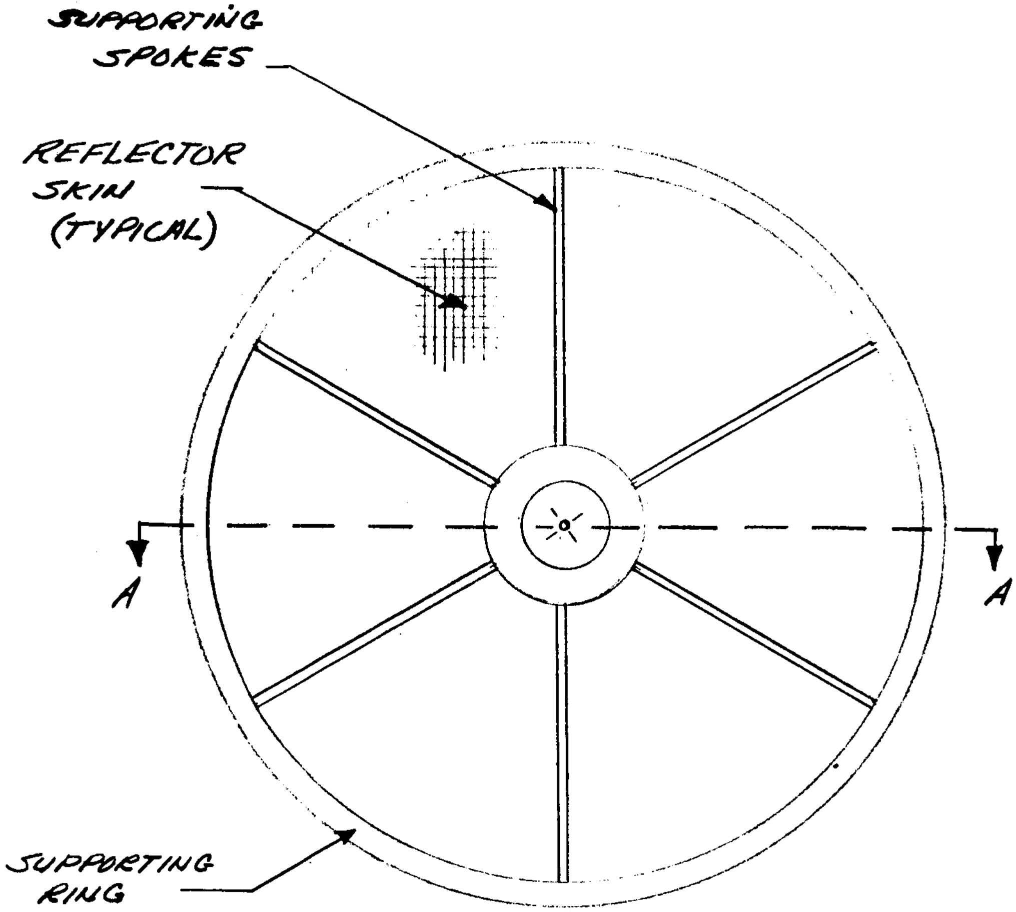


FIGURE 8. REFLECTOR DIAMETER VERSUS GAIN AND MASS



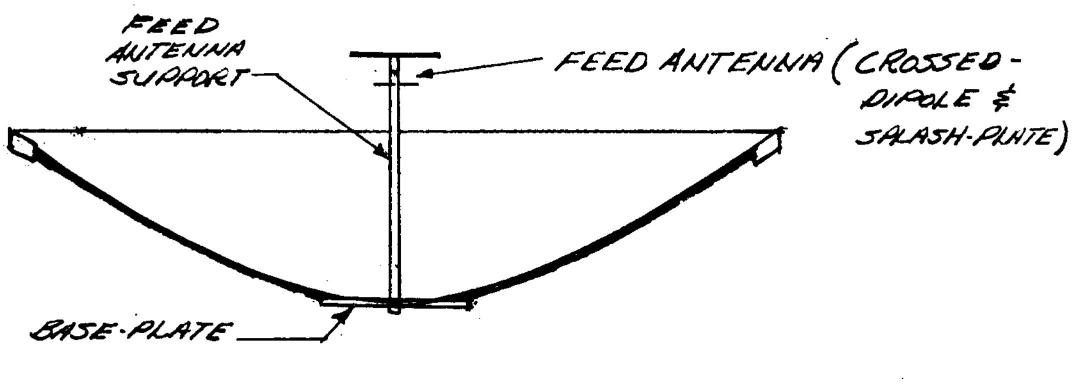


FIGURE 9. PARABOLIC ANTENNA MODEL FOR MASS CALCULATION

The mass of the skin or reflector surface will be:

Mass Skin = Area . Thickness . Density . Porosity

The area will be considered for calculation purposes, to be a flat plate, with a 0.076 cm (0.03 in.) thickness. Aluminum will be used throughout as the material of fabrication. The density of aluminum is 2680 kg/cu. meter (167 lbs/cu. ft.).

A porous or meshed-type reflector surface will be considered. The primary purpose of this type of construction will be to reduce the mass of the antenna. Several secondary advantages of the porous surface may be realized, including the decrease of micrometeorite impact probability rates, and, through proper design, the decrease of thermal stresses which are generated in the antenna due to the temperature differential between the inside and outside surfaces.

Electrically, the surface is insensitive to these perforations, as long as certain design requirements are adhered to. If a wire screen with square openings makes up the reflector surface, the edge length (ℓ) of the openings must be made in such a way that

$$\ell < \frac{\lambda}{\sqrt{2}}$$

For calculation purposes, a mesh or porosity factor of 0.5 (one-half of the surface material removed) is used.

The mass of the reflector skin will be:

$$W_{skin} = .8D^2 \quad \text{(D in meters)}$$

The basic mass of the feed antenna will not vary with the reflector diameter, but will, in essence, remain constant. A practical mass value for this feed antenna is 0.23 kgs (.5 lbs.).

$$W_{feed} = 0.23 \text{ kg}$$

The support for this feed antenna will vary directly with the diameter, since the F/D ratio is fixed at 0.3. A reasonable value for this support increase is 0.75 kg per meter (0.5 lbs/ft.).

$$W_{feed\ support} \cong (.3)\ (.75)D = .225D \text{ kg}$$

The supporting spokes will vary as described. If a uniform cross-section of 0.322 cm^2 ($\frac{1}{2}$ in.sq) is considered, the mass will be:

$$W_{spokes} \cong \text{AREA . LENGTH . DENSITY}$$

Essentially, in the configuration shown, there are three spokes which vary in mass with the diameter or length.

$$W_{spokes} \cong 1.35D \text{ kg}$$

The outer supporting ring is a function of the reflector circumference, or πD. The mass again will be:

$$W_{ring} \cong \text{AREA . DENSITY . LENGTH}$$

or, assuming a 1.27 cm by 2.54 cm ($\frac{1}{2}$ in by 1 in) cross section,

$$W_{ring} = 2.7D \text{ kg}$$

The base-plate, used for mounting the antenna to the rotator, will have an assumed constant thickness of 0.635 cm (0.25 in) and will have a diameter equal to 0.2 times that of the reflector. Thus the mass of this base-plate will be

$$W_{base\ rate} = \text{AREA} \cdot \text{THICKNESS} \cdot \text{DENSITY}$$

or $W_{base\text{-}plate} \simeq 0.54\ D^2$ kg

Summing these sub-system mass to obtain the total composite antenna mass will produce the following expression:

$$W_{antenna} = 1.34\ D^2 + 4.3\ D + 0.23$$

This expression is plotted in Figure 6.

It must be noted that the mass of the rotator or drive system is not included in this expression for antenna mass . The mass of the drive system, and also the supporting pylon, will not only be a function of antenna size (mass), but also of the torque required, the speed of movement necessary and the amount of pitch and roll of the MOLAB vehicle.

Thus far, the following expressions have been assembled:

1. Total effective radiated power (ERP) is the product of transmitter power (watts) and antenna gain (ratio).

$$P_T = ERP = P_x\ G_A \text{ (watts)}$$

or $$ERP_{(dbw)} = P_{x(dbw)} = G_{A(db)}$$

2. Total mass is the sum of transmitter mass and antenna mass (excluding the drive system).

$$W_T = W_x + W_A$$

3. Power output of the transmitter as a function of mass (state-of-the-art for 10-to-200 watts) is shown by:

$$P_x = 25W_x - 135 \quad \text{(mks)}$$

$$P_x = k_1 W_x - k2$$

4. Gain of antenna (parabolic reflector) is shown by:

$$G_A = 350\ D^2 \quad \text{or} \quad G_A = k_3\ D^2$$

$$G_A(\text{db}) = 10 \log_{10} 350\ D^2$$

5. The mass of the antenna is shown by:

$$W_A = 1.34\ D^2 + 4.3D + 0.23$$

$$W_A = k_4 D^2 + k_5 D + k_6$$

It is desirable to solve for the optimum transmitter power at a minimum system mass for some predetermined total power (ERP) required by the system. This total power (P_T or ERP) can be obtained from the following equation once the required parameters of base bandwidth and carrier-to-noise levels are fixed.

$$P_T = P_x G_A = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{k\ T_E\ B \cdot S/N \cdot L.S.F.}{G_R}$$

See section 2 for an explanation of terms.

The mass of the transmitter is:

$$W_x = \frac{P_x}{k_1} \qquad \frac{k2}{k_1}$$

and, substituting in the equation $W_T = W_x + W_A$,

$$W_T = \frac{P_x}{k_1} + \frac{k_2}{k_1} + k_4 D^2 + k_5 D + k_6$$

but

$$D^2 = \frac{G_A}{k_3} \quad \text{and} \quad G_A = \frac{P_T}{P_x}$$

thus $D^2 = \dfrac{P_T}{k_3 P_x}$

$$W_T = \frac{P_x}{k_1} + \frac{k_2}{k_1} + \frac{k_4 \, P_T}{k_3 \, P_x} + k_5 \left(\frac{P_T}{k_3 P_x}\right)^{\frac{1}{2}} + k_6$$

or, writing in another form:

$$W_T = k_A \, P_x + k_B P_T P_x^{-1} + k_C P_T^{\frac{1}{2}} P_x^{-\frac{1}{2}} + k_D$$

where

$$k_A = \frac{1}{k_1}; \quad k_B = \frac{k_4}{k_3}; \quad k_C = \frac{k_5}{k_3^{\frac{1}{2}}}$$

and $K_D = \dfrac{k_2}{k_1} \quad k_6$

Taking the derivative of W_T with respect to P_x and setting it equal to zero will give the transmitter power required for a minimum system mass and fixed ERP.

$$\frac{d\,W_T}{P_x} = 0 = k_A - k_B P_T P_x^{-2} - \frac{k_C \quad P_T^{\frac{1}{2}} P_x^{-3/2}}{2}$$

$$0 = 4 \times 10^{-2} - 3.8 \times 10^{-3} \, (P_T) \, (P_x^{-2}) - 1.15 \times 10^{-1} \, (P_T^{\frac{1}{2}}) \, (P_x^{-\frac{3}{2}})$$

Substituting the proper numerical values for the constants and a value of 4×10^3 watts (36dbw) for P_T, shows that a transmitter power level of approximately 40 watts (16 dbw) is required for optimum system mass (a combination of transmitter and antenna mass). An antenna gain for this power combination is:

$$G_A = \frac{P_T}{P_x} \quad \frac{4 \times 10^3}{4 \times 10^1} = 1 \times 10^2$$

or $G_A(\text{db}) = 10 \log_{10} 10^2 = 20$ db

This antenna gain requires an antenna 0.525 meters in diameter.

$$D^2 = \frac{Ga}{3.5 \times 10^2} = \frac{10^2}{3.5 \times 10^2} = 0.276 \text{ meter squared}$$

$$D = 0.2525 \text{ meter } (1.73 \text{ feet})$$

Thus the masses of the transmitter and antenna will be:

$$W_x = \frac{P_x + 135}{25} \qquad \frac{40 + 135}{25} = 7 \text{ kg}$$

$$W_A = 1.34\, D^2 + 4.3\, D + 0.23 = 0.37 + 2.25 + 0.23 = 2.85 \text{ kg.}$$

$$W_T = W_x + W_A = 7 + 2.85 = 9.85 \text{ kg } (22 \text{ lbs})$$

The total effective radiated power (36 dbw), used in the above calculations, is based on an S-Band RF transmitting link with a base bandwidth of 1.0 mcps, a 16 db carrier-to-noise level and a 30 db receiver signal-to-noise ratio at an FM modulation index of 2. These are realistic values for an appreciable high resolution TV system for the MOLAB-to-earth communications link.

7.0 S-BAND LUNAR SURFACE RELAY LINK

7.1 LUNAR COMMUNICATIONS

It is desirable to provide an S-Band communication link on the lunar surface. This link is to be used for transmitting and receiving information between points A and B on the lunar surface. These points may be the LEM vehicle and the MOLAB or possibily the MOLAB and a roving astronaut.

Two systems can be realized. These are a passive system of stations and an active system of repeaters.

The passive system has many disadvantages such as a high initial power and a loss at each point of relay and alignment due to narrow beam antennas; therefore, it is not feasible at this time.

The active system of a transmitter and a receiver at each relay station was studied.

At this frequency band (2300 mcps), line-of-sight communication is the only feasible approach.

7.2 LINK PARAMETERS

It is desirable to utilize an existing transponder for this study. The Motorola Mark I S-Band Transponder, which has been designed for the Mariner "C" usage, was chosen because it may be used for the Apollo mission.

The characteristics of this transponder are:

Receiver Frequency	2113.3 mc
Transmitter Frequency	2295 mc
Transmitter Power	0.5 watts
Modulation	PM d.c. to 1.8 mc
Bandwidth	1.8 mc
Noise Figure	11 db
Carrier Sensitivity	-150 dbm
Input Power	13 watts
Mass and Cubage	43.03 kg/4900 cm^3
	(95 lbs./300 $in.^3$)
Dimensions	35.56 cm x 17.78 cm x 7.62 cm
	(14 in. x 7 in. x 3 in.)
Temperature: Operational	-10° C to +75°C
Storage	-65°C to +125°C

Due to the small radius of curvature of the moon, line-of-sight distances are extremely short; therefore, towers will have to be used for extending the range distances.

Tower:

	STATION A	STATION B	RANGE
Tower 0.00 m	(0 ft.)	0.0 m (0 ft.)	.804 km (1/2 mile)
Tower 4.56 m	(15 ft.)	0.0 m (0 ft.)	4.02 km (2.5 miles)
4.56 m	(15 ft.)	4.56 m (15 ft.)	8.04 km (5 miles)
9.12 m	(30 ft.)	9.12 m (30 ft.)	11.26 km (7 miles)
18.24 m	(60 ft.)	1.824 m 6 ft.	10.45 km (6.5 miles)
18.24 m	(60 ft.)	18.24 m (60 ft.)	16.45 km (6.5 miles)
30.24 m	(100 ft.)	30.24 m (100 ft.)	20.8 km (12.9 miles)

Since tower heights greater than 18.24 m (60 ft.) do not seem practical, a height of 18.24 m (60 ft.) and a range of 16 km (10 miles) was chosen as an optimum value.

The 18.24 (60 ft.) tower (STEM DeHavilland Design) will support, at the top, 18 kg (40 lbs, earth weight) with one end of the tower fixed for a 7.62 cm (3.0 in.) diameter tower. This mast is fabricated of stainless steel tubing with a 0.013 cm (0.005 in.) wall thickness. No mass information is available at the moment, but an approximate mass is calculated below:

$$\text{Tubing weight} \approx \pi \frac{(\text{D outside} - \text{D inside})^2}{4} (\text{Height})(\text{Density of Steel})$$

$$\approx 3.4 \text{ kg } (7.5 \text{ lbs})$$

Since this mass represents only that of the tubing, additional components of the tower, such as stiffening rings, top and base plates, a stabilizing spike, and an erection device will make up the total tower mass . A very rough estimate of 4.5 kg (10 lb) will be used at the moment for the tower mass . (A more accurate value will be available with research on the subject, as will information on packaging dimensions).

7.3 LINK CALCULATIONS

Parameters for determining the required antenna characteristics (gain, etc.), and using the Motorola Mark I transponder are as follows:

$$P_T = \left(\frac{4\pi R}{\lambda}\right)^2 \frac{kTB}{G_R\ G_T} \frac{(N.F)\ (S/N)\ (S.F.)}{10^{-3}\ (\text{for dbm})}$$

P_T	500 mw (fixed by transponder)	+27 dbm
Path loss	$\left(\frac{4\pi R}{\lambda}\right)^2$ R = 16 km	+124 db
ktB	T = 200°K, B = 500 k cps	-148.5 db
N.F.		+11.db
S/N		+10 db
S.F.		3 db
Conversion to dbm		30 db
G_R Receiver Antenna		+1.25
	Calculated	
G_T Transmitter Antenna		+1.25

These calculations show that the transmitter power of 500 mw (27 dbm) is adequate for the 16.09 km (10 mile) range when antenna gains of 1.25 db are used for the transmitting and receiving antenna. These gain values are based on a 0.5 mcps bandwidth. If the wider bandwidth capability (1.8 mcps) of the transponder is utilized, antenna gains of 4 db are necessary.

7.4 ANTENNAS

Antenna gains of the calculated values above are easily obtained. A halfwave dipole has a 2.1 db gain, referred to an isotropic radiator.

It is desirable, for this system of relays, to use a more directional antenna, thus reducing the chances of coupling between relay stations. An antenna with 10 db gain ($50° \pm 3°$ half-power beamwidths) will produce the desired coverage.

These antenna gains would require less power from the transmitter for a 16.09 km (10 mile) range, but for study purposes, the 500 mw power level of the transponder will be used.

Various antenna configurations feasibly could be used as transmitting and receiving antennas. Some possibilities are: parabolic reflector and feed, yagi, conical and rectangular horns, and helical antennas.

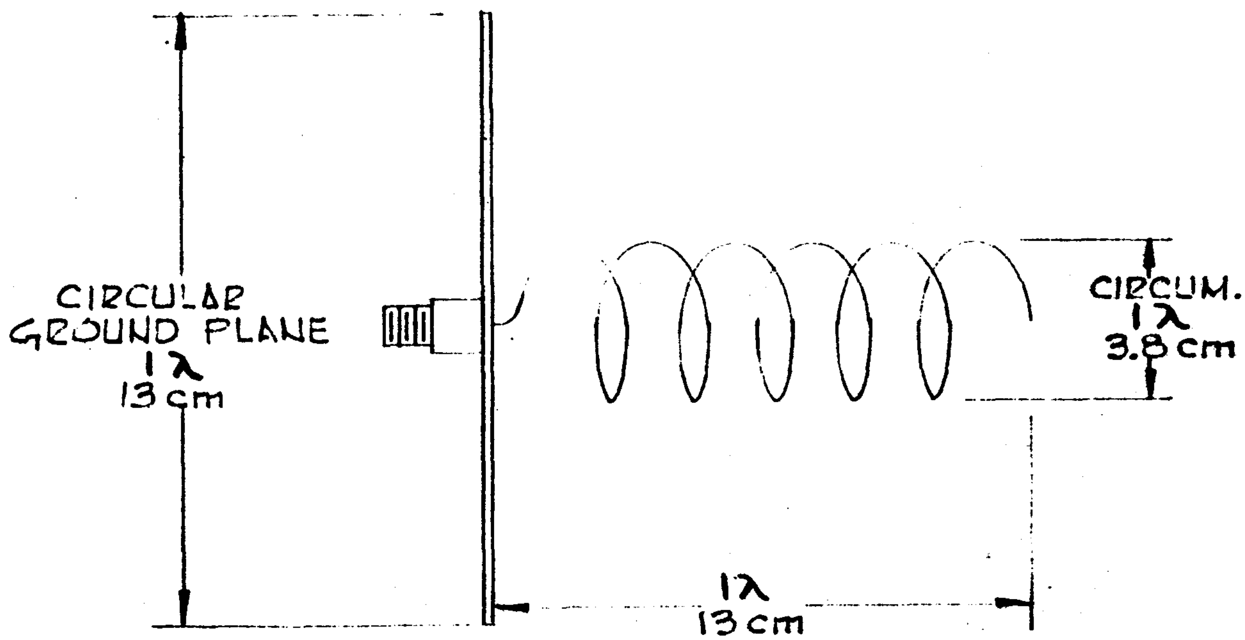
It is highly desirable, if not required, that circular polarization be used in the antenna system, as circularly polarized antennas are unique in being unable to see their own image (regarding RF) in any symmetrical reflecting surface. This characteristic is due to the phase reversal (180°) of the horizontal component in the RF wave, reversing the sense of the reflected wave from, for example, a right-hand circular to a left-hand circular. Any reflection or interaction of a reflected wave from the lunar surface, therefore, is reduced approximately 30 db. This reduction is a function of a reflecting surface and the degree of ellipticity of the antenna beam. Analysis of the various antennas is necessary in order to optimize weight, package, and gain parameters.

A 15.24 cm (6 in.) parabolic reflector produces approximately 10 db gains, a 30.48 cm (12 in.) parabolic reflector produces a 15 db gain; both will have a crossed dipole feed for circular polarization. A system of this type (dish and feed) can be fabricated by using techniques which will produce a compact and lightweight package.

Horn antennas also may be fabricated of lightweight metals, but compact packaging may present a problem area.

The helical antenna seems to be the logical antenna for the system under consideration. State-of-the-art fabrication techniques are capable of producing extremely lightweight, collapsible antennas of recoverable foam, which require very little space.

The helical antenna is inherently circularly polarized, and has constant gain and beamwidth over a broad band; hence, the same antenna may be used for transmit and receive frequencies (2113 mc and 2295 mc), utilizing good design techniques. A helical antenna, to provide a gain of (10 db), should have a maximum mass of 0.109 kg (1/4 lb.). A typical dimensional layout of the described helical antenna is shown below:



7.5 POWER SUPPLY

The power supply incorporated in this system shall be capable of continuous operation to supply environmental control to the associated equipment.

Mass, as in all space equipment, is a prime factor. In this application, the antennas and transponder will be located at the top of an 18.24 m (60 ft.) tower, as cable mass and cabling losses will be too large if the transponder is located at the base of the tower. It is, therefore, necessary to locate the power supply at the top of the tower for environmental control of the transponder.

A snap-11A (Martin-Marietta Corporation) type power supply, with an isotope of longer half-life seems to be ideal as to mass and power capability. This unit has a mass of approximately 13.59 kg (30 lbs.) and produces 25 watts. The physical package measures 30.48 cm (12 in.) in height and 50.80 cm (20 in.) in diameter. The basic cost of a unit of this type is unknown at this time.

7.6 SYSTEM

Each relay station will consist of two antennas, a 18.24 m. (60 ft.) tower, a transponder, a power supply, and environmental control equipment. Individual relay station parameters of mass, cost, and package dimensions are outlined as follows:

Antenna: (Transmit and Receive)

Type: 11 db gain collapsible helix

Package:

Storage: 12.70 cm (5 in.) diameter ground plane
3.81 cm (1.5 in.) x 12.70 cm (5 in.)
long (radiating element)

Mass : 0.113 kg/unit (0.25 lbs/unit)

Cost: $200.00/unit

Environmental Limits: -155°C to +120°C)

Transponder:

Type: Motorola S-Band Mark I

Package: 34.80 cm x 16.0 cm x 11.17 cm (13.7 in x 6.3 in. x 4.4 in.)

Mass : 4.07 kg (9 lbs.)

d.c. Power Input: 13 watts +15v & -25v

RF Power Out: 0.5 watts @ 2295 mcps

Environmental:

Storage: -65° to +125°

Operational: -10° to +75°

Cost: $60 k

Power Supply:

Type: SNAP 11-A

Package: 30.48 cm (12 in.) long $\rightarrow$ 50.80 cm (20 in.) O.D.

Mass : 13.59 kg (30 lbs)

Power-out: 25 watts

Cost: Unknown at this time

Tower:

Type: DeHavilland STEM

Package:

Storage:

Operational: 18.24 m (60 ft.) x 7.62 cm (3 in.) diameter

Mass : 4.5 (10 lbs.)

Cost: $\approx$ \$8 k

Environmental: -155° C to +120°C

Total mass requirement for each tower relay will be:

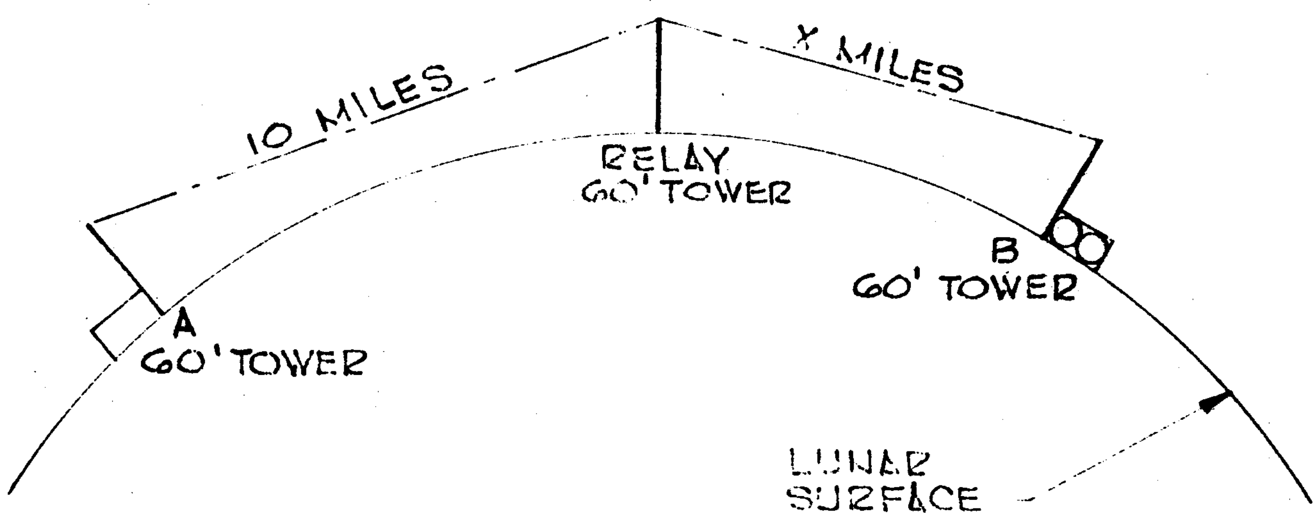
Mass: Total $\approx$ (2 antennas) + (Transponder) + (Power Supply) + (Tower)

$$W_T = .113 + 4.06 + 13.6 + 2.26 = 20.1 \text{ kg}$$

7.7 SYSTEM INSTALLATION

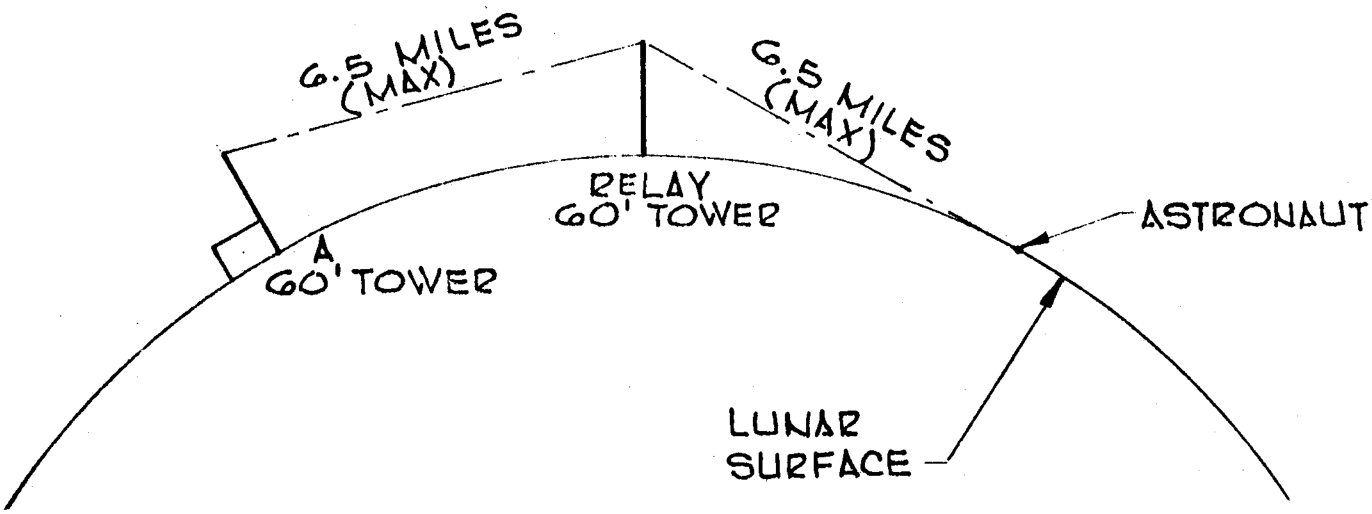
It has been shown that a line-of-sight range of 16.09 km (10 miles) can be covered by using 18.24 m (60 ft.) relay towers, with antennas and associated equipment mounted on top of these towers.

The preceding study of parameters is based upon transmission betwe... two established points, such as (A) a lunar shelter and (B) a lunar vehicle, both having antennas mounted 18.24 m (60 ft.) above the lunar surface. The erection of a relay tower at 16.09 km (10 mile) intervals of separation would allow an indefinite communication range.



The situation changes considerably if the two points of interest (A) and (B) are, for example, a lunar shelter or lunar vehicle (A) and a roving astronaut (B).

The average astronaut, having a height of 1.82 m (6 ft.), would find the line-of-sight range from a 18.24 m (60 ft.) tower to be between 10.45 and 11.26 km (6.5 and 7 miles). He therefore would be required to erect a 18.24 m (60 ft.) tower each 10.45 km (6.5 miles) to further increase his communications capability.



(1) Range of communication between fixed stations = 10 (number relays) + 16.09 km (10 miles).

(2) Range of communication between astronaut & fixed station = 6.5 (number relay) + 10.45 km (6.5 miles).

7.8 ACCURACY IN RELAY LOCATION

The accuracy in location of the relay points requires some consideration, as many variables exist.

It has been assumed in the range determination that a flat (smooth) terrain exists. If an irregular (mountainous) terrain exists, the range will be dependent upon the degree of irregularity.

7.9 ANTENNA BORESIGHTING

The degree of freedom allowed in positioning the antennas on the towers is subject to the itinerary of the vehicle or astronaut.

If an antenna of the outlined type (10 db gain, and 3 db beamwidths of 50 $\pm$ 3 degrees) is utilized, the half-power (3 db) beamwidth will cover an area of approximately $\pm$ 6.43 km (4 miles) off boresight for a 16.09 km (10 miles) range, and $\pm$ 4.82 km (3 miles) off boresight for a 10.45 km (6.5 mile) range.

This would allow the astronaut or vehicle an appreciable amount of latitude in maneuvering between terrain irregularities.

7.10 CONCLUSIONS

An S-Band (2300 mc) relay system of towers providing a 16.09 km (10 mile) extension of range (per relay station) between two fixed stations (A and B) would have a mass of approximately 20.38 kg (45 lbs.) per relay station.

This relay link would provide a roving astronaut 10.45 km (6.5 miles) additional range per relay station.

Coupling between relay stations should not present a problem on a semi-straight link, but could present a problem on figure eight links. This is dependent upon itinerary and relay location.

7.11 LUNAR BASE AND VEHICLE SYSTEMS

The equipment required for the roving vehicle or lunar shelter can be the same as that used for the relay tower, although this would be highly impractical since considerable duplication of equipment would result. The existing power supply of the vehicle and base station, which forms the bulk of mass and cost of the relay system, can be utilized.

The transponder may be the same unit (Mark I), or possibly equipment used on another link. This unit can be located internally at the station, thus eliminating environmental control requirements which exist at the relay stations, assuming that environmental control is provided at all times in the station.

The same procedure may be used in tower installation, although mass requirements may be reduced somewhat, as the station and vehicle can be utilized as a mounting platform. It will be necessary to provide RF cable to the antennas located at the top of this tower. If "low loss cable" such as Spiro-form is used, losses of approximately 3 db will occur.

the 500 mw transmitter is adequate to compensate for this loss in power at the antenna terminals.

7.12 ASTRONAUT SYSTEM

The system necessary for the astronaut to communicate with the base station and relay information via the relay towers will consist of the following equipment.

He will be required to have an antenna, preferably mounted on a light-weight tripod for positioning; a transmitter compatible with bandwidth requirements of the system; a receiver capable of voice reception; and a power supply capable of 20 watts output to supply transmitter, receiver and environmental control power.

It will be necessary to provide the astronaut with some form of environmental control and a possible power supply for a TV camera. Therefore, the additional mass of a power supply to the power communication system should be small.

8.0 S-BAND (VOICE) LINK

The preceding study was based on the use of an existing S-Band transponder, which has the capability of video communication.

It now is desirable to study the parameters of a system of relays for lunar surface communications where voice data is the sole requirement. The maximum bandwidth under consideration is 2.5 k cps.

A line-of-sight range of 10 km (6.25 miles) will be assumed as the maximum range between relay stations.

Tower heights for line-of-sight communications at this range will be:

> 9.12 m (30 ft.) each station - 10km (6.25 miles)
>
> 9.12 m (30 ft.) one station & 1.82 m (6 ft.) astronaut - 8.04 km (5 miles)
>
> 18.24 m (60 ft.) one station & 1.82 m (6 ft.) astronaut - 10 km (6.25 miles)

The type of antenna used for transmitting and receiving will be the same as outlined in the preceding study. It will be a circularly polarized helical antenna of 10 db gain and will have a half-power beamwidth of $50° \pm 3°$.

8.1 LINK PARAMETERS

The transmitter power required from the transponder will be calculated by using the varied parameters of range (10 km) and bandwidth (2.5 kc.). The other parameters, noise figure (NF), and signal-to-noise ratio (S/N), which are dependent upon transponder design, may vary in practice, but previous values will be used for comparison study purposes.

P_T	Calculated 0.02 mw	-17.9 dbm
Path loss	$\left(\frac{4\pi R^2}{\lambda}\right)$, R=10 km, f=2300 mc	119.7 db
kTB	T=200°k, B=2.5 kc	-171.6 dbw
NF		11 db
S/N		10 db
S.F.		3 db
G_R		+10 db
G_T		+10 db
dbw to dbm		30 db

A transponder, to produce the necessary transmitter and receiver characteristics: power, bandwidth, etc., should require approximately 3 watts of input power. Packaging of the unit will not present a problem, as mass is approximately 2.26 kg (5 lbs).

8.2 POWER SUPPLY

A small SNAP unit is a possible means of supplying power. Approximately 5 watts electrical power will be required for transponder and environmental control under full load conditions. A SNAP unit of this output requirement should be easily designed; a reduction in mass will be evident with lower ampere-hour cells. The mass of such a SNAP unit will be approximately 4.53 kg (10 lbs.).

An alternate approach is under study in which mercury cells with no recharge capability will be used as the power supply. Information on mercury cell characteristics, life expectation, mass for required power output, environmental requirements (operational and storage), and cost, are necessary to evaluate their usage.

The possibility of utilizing mercury cells as power supplies for short duration relay links warrants further study, although the SNAP unit offers the advantage of rechargeable cells and long term usage. The SNAP system will be utilized in this study

8.3 TOWER

As shown previously, tower heights of 9.12 m (30 ft.) are adequate for line-of-sight communication over the 10 km (6.25 mile) range. (This again is assuming a smooth lunar surface). The range between a 9.12 m (30 ft.) tower and 1.82 m (6 ft.) astronaut will be 8.04 km (5 miles). Towers, therefore, will be placed at 10 km (6.25 mile) or 80.45 km (5 mile) intervals, depending on relay usage.

A 2.54 cm (1 in.) diameter tower (DeHavilland STEM design) will be adequate for the package weight under consideration: approximately 6.79 kg (15 lbs).

Tower mass should be approximately 2.26 kg (5 lbs.)

8.4 SYSTEMS MASS

The system (relay tower) will consist of the following components:

Antennas 2/units @ 0.11 kg (0.25 lbs) each	0.23 kg (0.50 lbs)
Transponder	2.26 kg (5.0 lbs)
Power Supply (SNAP unit)	4.53 kg (10.0 lbs)
Tower 9.12 m (30 ft.) 2.54 cm (1 in.) O.D.	2.26 kg (5.0 lbs)
TOTAL	9.28 kg (20.5 lbs)

8.5 SYSTEM COST

Final cost of this system should be considerably less than the system previously outlined, but developmental costs will need to be considered.

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7. Literature Search - Technical Publications

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